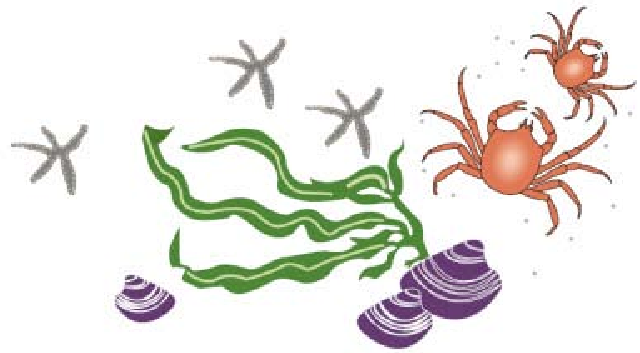
AN INTRODUCTION
to COASTAL HABITATS and BIOLOGICAL RESOUR for OIL SPILL RESPONSE



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to Coastal Habitats and Biological Resources

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Introduction

We will discuss the physical, geological, and biological considerations relevant to oil behavior and oil spill response and cleanup. The questions which we will address include:

- How does the physical environment affect the impacts of an oil spill on a shoreline?
- What factors affect the behavior and toxicity of oil?
- What kinds of shorelines are most at risk from an oil spill, and why?
- What are the effects of oil exposure on biological resources?
- What kinds of techniques are available for treatment of oil spills?
- How are the impacts of oil and cleanup assessed and monitored?
- What are the tools that are available for assisting response personnel in evaluating resource impacts?
- What are the important lessons from previous spills?

The response and cleanup techniques that we will discuss have, as their ultimate goal, the minimization of impacts from oil spills. To realize this goal, it is important to have a basic understanding of how each of the components covered in this course interrelate. It is our intent that readers understand the role that each set of considerations—physical, chemical, geological, and biological—plays in determining both the route and degree to which the goal is attained. We will try to pass on the lessons of previous experience and research, and to provide a foundation on which insights and knowledge can be added as time goes on. Ultimately, we hope that this will contribute to an informed and effective oil spill response in coastal waters.

1 The Coastal Environment

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Chapter 1.
The Coastal Environment

Introduction

This chapter presents the physical controls and attributes of coastal habitats as preparatory material for understanding how they may be impacted by an oil spill. The discussion begins with a brief review of the geological forces, such as plate tectonics and continental glaciation, that have shaped the primary framework of the coastal systems. Also given is an introduction to the dynamic coastal processes that shape the detailed configurations of the habitats, as well as a description of the origin and nature of sediment types and water/sediment (and potentially oil) interactions in certain specific environments, such as estuaries and sand beaches.

Coastal Morphology

Introduction

The morphology of a coastline provides the basic framework to which other relevant factors, such as biological habitat and physical processes, are tied. Therefore, a general knowledge of the coastal morphology of the spill site is of primary importance in planning the response to a spill. For example, a young mountain range coast backed by cliffs in bedrock with beaches of coarse gravel presents an entirely different set of problems than does a low-lying coastal plain shoreline with abundant mud flats and salt marshes. The morphology of coastlines is determined by five primary controlling factors:

1) Global tectonic crustal movements
2) Hydrodynamic regime
3) Sediment supply and sources
4) Climate
5) Local geological history and sea-level changes

Each of these controls will be considered separately.

Global Tectonics

A most important aspect of any coastal region is whether it is rising, sinking, or essentially stable—that is, its tectonic setting. In a study of the widths and slopes of continental shelves, Hayes (1964) classified the shorelines of the world into the categories given below:

Class	Tectonism	Examples
A) Tectonic coasts		
1) young mountain range coasts	- Rapid uplift	- California; Alaska; western South America
2) glacial rebound coasts	- Rapid uplift	- Eastern Canada; Norway
B) Plateau-shield coasts	- Relatively stable	- India; West Africa; central Brazil
C) Depositional coasts	- Downwarp	- Gulf and East Coasts of the United States

Definitions of these shoreline classes follow:

<u>Young mountain range coasts</u>: Coastal zone made up of high mountains (maximum elevations greater than 5,000 feet) related to Cenozoic orogenic activity (<±50,000,000 years ago). Bedrock of variable age but principally Tertiary sediments and volcanic rocks. Active tectonic uplift. Mostly short, high-gradient rivers emptying into the sea.

<u>Plateau-shield coasts</u>: Coastal zone made up of plateaus and moderate mountain ranges related largely to pre-Cenozoic orogenic activity. Bedrock composed of ancient basement complexes of granite and gneiss (in shield areas) and Paleozoic, Mesozoic, and Tertiary sediments (in plateau areas). Plateaus formed on complex suites of volcanic rocks are also present and the area is tectonically stable (relative to young mountain range and depositional coasts). Numerous moderately long rivers may be present, depending on climate.

Depositional coasts: Coastal zone made up chiefly of broad coastal and deltaic plains. Bedrock generally Tertiary and Quaternary sediments. Tectonically subsiding area. Many long, large rivers emptying into the sea.

Glacial rebound coasts: Coastlines undergoing uplift because of isostatic readjustment of the earth's crust after removal of the load of the continental ice sheets at the end of the last major glaciation (Wisconsin, 10,000-14,000 years Before Present [B.P.]).

Genetically, these shoreline types are closely related to plate tectonics. The simplest distinction, on the basis of plate tectonics, is between leading edge and trailing edge coasts (Fig. 1-1). Leading edge, or collision, coasts have roughly the same characteristics as young mountain range coasts (as defined above), whereas trailing

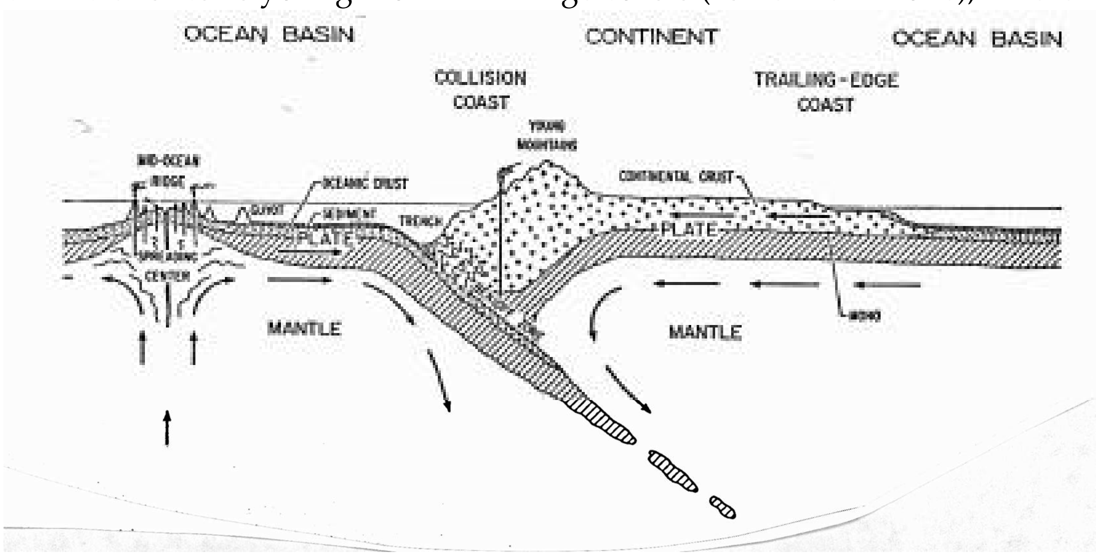

Figure 1-1. Diagrammatic representation of a section through collision and trailing edge coasts. Arrows indicate the direction of movement of crustal plates. (After Inman and Nordstrom, 1971; Fig. 2.)

edge coasts usually have the characteristics of depositional coasts. Inman and Nordstrom (1971) treated this subject in considerable detail and proposed the following major classes:

1) <u>Collision coasts</u>—formed where two plates converge.
   a) Continental collision coasts—where a continental margin is located along the zone of convergence.
   b) Island arc collision coasts—where no continental margin is located along the zone of convergence.
2) <u>Trailing edge coasts</u>—where a plate-imbedded coast faces a spreading zone.
   a) Neo-trailing edge coasts—where a new zone of spreading is separating a land mass.
   b) Afro-trailing edge coasts—where the opposite continental coast is also trailing.
   c) Amero-trailing edge coasts—where the opposite continental coast is a collision coast.
3) <u>Marginal sea coasts</u>—where a plate-imbedded coast faces an island arc.

As a general rule, the collision coasts are characterized by steep, rocky shores and coarse-grained sediments. Wave energy is usually high. Neo- and Afro-trailing edge coasts are of the plateau-shield variety, usually being very complicated shorelines with scattered pocket beaches, some cliffed shorelines, and a variety of other features. Amero-trailing edge coasts and marginal sea coasts are usually dominated by coastal plain shorelines composed of river deltas and barrier islands. Most of the East and Gulf coasts of the USA shoreline fall in the Amero-trailing edge category. The coasts of Washington, Oregon, California, and the south coast of Alaska are continental collision coasts. Much of the rest of the Alaskan coast is a complex marginal sea coast.

Hydrodynamic Regime

Introduction

Following the pioneer work of W.A. Price (1955), we have concluded that the most important control of the morphology of coastal plain shorelines (primarily found on trailing edge and marginal sea coasts) is the type and amount of hydrodynamic energy expended within an area; furthermore, with some exceptions, the two energy factors of most significance, wave energy flux and tidal energy flux, can be related directly to **tidal range**. Davies (1964) and Hayes (1965) classified shorelines, as follows, on the basis of tidal range:

Class	Tidal Range*
Microtidal coasts	0-2 m
Mesotidal coasts	2-4 m
Macrotidal coasts	>4 m

*To be exact, Davies' boundaries were 0-6 ft, 6-12 ft, and >12 ft, and Hayes' were 0-5 ft, 5-10 ft, and >10 ft. We have rounded off these numbers to the nearest whole metric unit. On the basis of study of details of coastal morphology on the coast of North America, we feel there is much justification for considering changing the mesotidal boundaries or perhaps splitting the mesotidal class into two categories; however, the boundaries proposed above will be maintained in these notes.

Generally speaking, coastal plain shorelines with small tidal ranges (microtidal) are dominated by wave energy, and coastal plain shorelines with large tidal ranges (macrotidal) are dominated by tidal currents and tidal-level fluctuations.

The reasons for this emphasis on tidal range is the fact that the effectiveness of wave action diminishes (i.e., waves cannot break in a concentrated area for a long period of time), and tidal current activity increases as the vertical tidal range increases. Of course, a small tidal range does not insure high wave energy, inasmuch as wave energy varies according to the fetch, average velocity, and duration of onshore winds in an area, as well as the incident swell.

On the basis of a study of coastal charts of the world (conducted at the Defense Research Laboratory, University of Texas), Hayes has compiled the distribution of coastal features versus tidal range. The distribution patterns of seven coastal features are shown in Figure 1-2. Note that river deltas and barrier islands are best developed in microtidal regions, whereas offshore linear sand ridges (built by tidal currents), tidal flats, and salt marshes are most abundant in macrotidal regions. Tidal deltas and tidal inlets are most abundant on mesotidal coasts. Further generalizations can be made about the interaction of wave parameters and tidal range. In fact, it is possible to designate three coastal plain shoreline types [(1) wave-dominated coasts, (2) mixed-energy coasts, and (3) tide-dominated coasts] on the basis of this interaction. Usually, wave-dominated coasts are microtidal; tide-dominated coasts are macrotidal; and mixed-energy coasts are mesotidal. There are

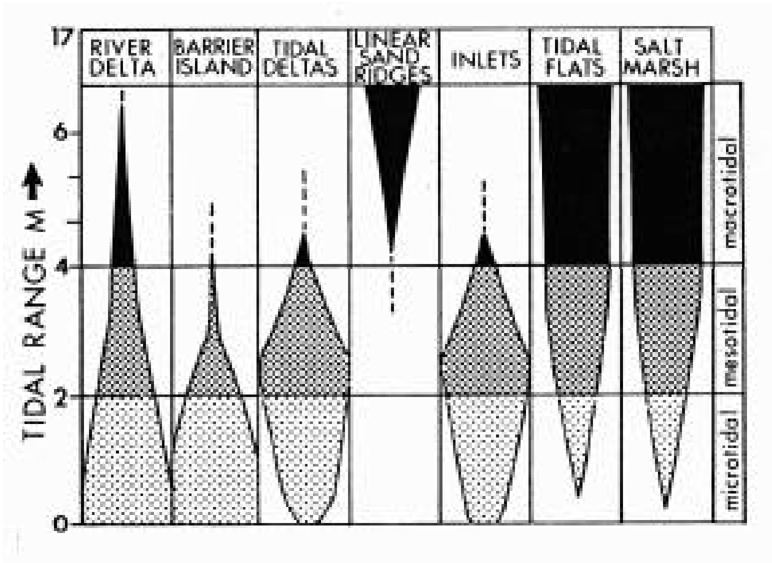

Figure 1-2. Variation of morphology of coastal plain shorelines with respect to differences in tidal range. (From Hayes, 1975; Fig. 1.)

exceptions. For example, a microtidal coast with smaller than normal waves may have the morphology of the typical mixed-energy coast (e.g., west coast of Florida). Therefore, it is the ratio of wave-energy flux to tidal-energy flux that ultimately determines the morphology of coastal plain shorelines.

Wave-dominated Coasts

River deltas with smooth, outer margins made up of sandy beaches occur at the mouths of major rivers on wave-dominated coasts. Between major rivers, long uninterrupted barrier islands are commonplace. Examples of coasts of this type include the Gulf Coast of the United States, the southern Baltic, southern Australia, and many other areas located on enclosed tideless seas, such as the Baltic and Mediterranean. These coasts are usually of the "barred coast" type; that is, a series of break-point bars parallel the beach. Sediment patterns of this model show a simple gradation in grain size from coarse to fine away from shore as a result of decreasing bottom agitation by waves with increasing water depth.

Tide-dominated Coasts

Along coasts occurring at the tide-dominated extreme of the hydrodynamic spectrum, the morphology at major river mouths consists mostly of open-mouthed estuaries. Deltas and barrier islands are inhibited in areas with large tidal ranges because of the tremendous erosive and transporting capacity of currents generated by the tides. Where deltas are present, they are usually of the multilobate type (e.g., Ganges-Brahmaputra Delta). Between major rivers, the coast is occupied by extensive salt marshes and tidal flats. Barrier islands are completely absent. Examples of this coastal type occur in northeast Australia, western Korea, the upper Bay of Bengal, the northern end of the Gulf of California, Cook Inlet, Alaska, the Wash (England), and at many other localities with tidal ranges greater than 4 m. Generally speaking, sediment patterns on coasts of this type are exactly opposite to those on wave-dominated coasts, inasmuch as finest sediments occur on mud flats of the upper intertidal zone, and coarsest sediments occur further offshore in zones where tidal currents prevail.

Mixed-energy Coasts

The intermediate type of coast on the hydrodynamic spectrum, where tidal energy flux and wave-energy flux are relatively equal, is the most complex of the three models. Modern examples include the South Carolina/Georgia coasts of the United States and the Wadden Sea coast of northwest Europe. Deltas are less well developed in this setting than on wave-dominated coasts. Between rivers, the barrier islands are short ("stunted"), and inlets are wide to allow for the large water exchange through the tidal cycle. Tidal deltas are large and numerous due to the occurrence of both strong tidal currents and wide inlets between the barrier islands. Sediment patterns are very complex, being controlled by the combination of wave action and tidal currents. The general model for this type of coastline is illustrated in Figure. 1-3.

Sediment Supply and Sources

Introduction

The nature of the beaches on many coastlines is highly dependent upon the volume and composition of sediments supplied to that shoreline. Where sediments are in abundance, beaches tend to accrete, building seaward, but where they are in short supply, beaches tend to erode, commonly causing damage to man-made structures built along the beach. Therefore, the <u>zone of sediment supply</u> is an important component of the coastal environment, and any change in it would greatly effect the evolution of the coastline. In most areas, the dominant source of sediments within

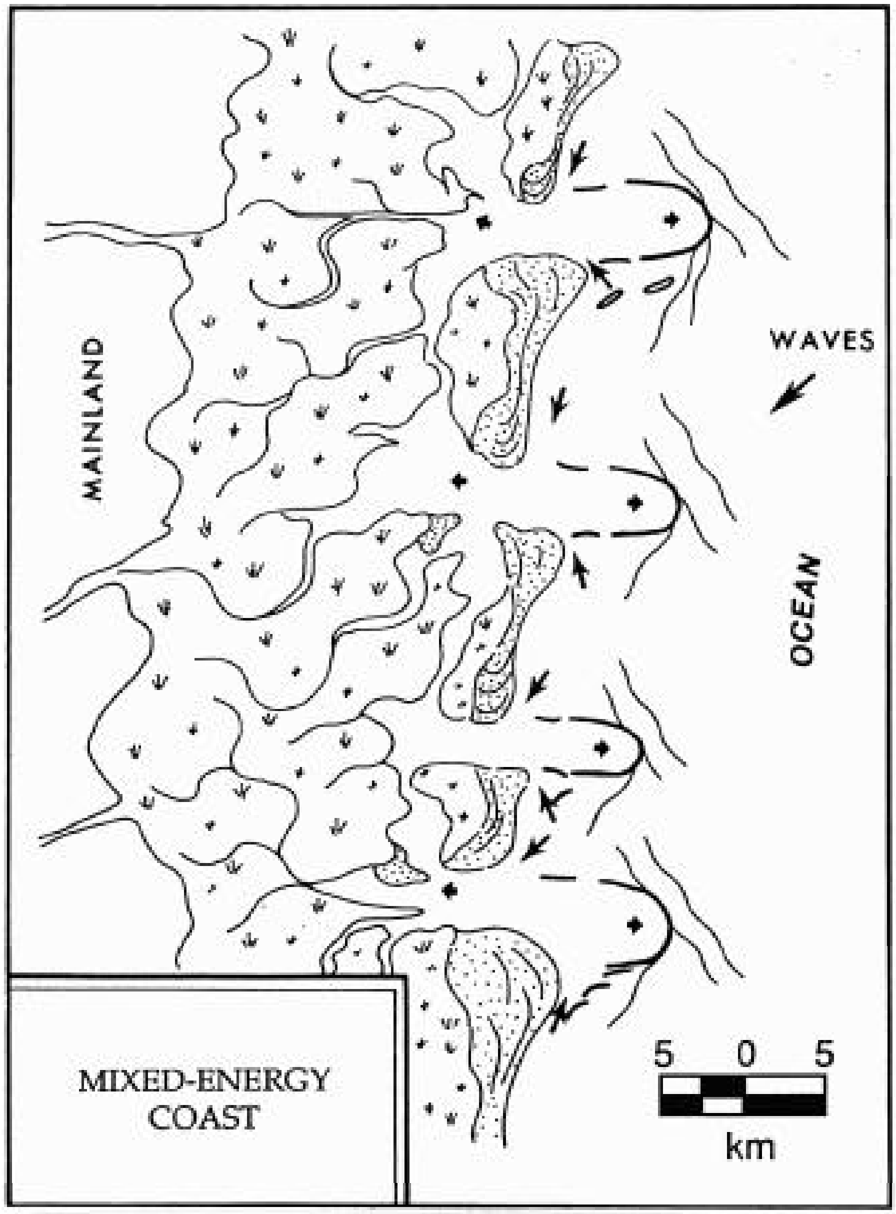

Figure 1-3. Characteristic morphology developed on a coastal plain shoreline (between major rivers) that has a mesotidal range (2-4 m) and average wave conditions, a mixed-energy coast. (From Hayes and Sexton, 1989; Fig. 44.)

the zone of sediment supply is the drainage network that carries sediments from the land areas to the shoreline. Other possible sources include: (a) material brought to the beach from remote segments of the coastline by longshore sediment transport; (b) erosion of rocky headlands or other portions of the shoreline adjacent to the beach; and (c) offshore marine sources, such as coral reefs, chemical precipitates, and shell-bearing organisms. Any of these potential sediment sources can be impacted by the activities of man. Studies on the coasts of California (Inman and Frautschy, 1966), Japan (Watanabe and Horikawa, 1983), and South Carolina (Hayes and Sexton, 1989) show that dams constructed along rivers that supply sediments to the shoreline have trapped large volumes of sand, causing severe beach erosion in those areas. Natural changes frequently impact the zone of sediment supply, as well, as the following two examples illustrate.

> **Mississippi River delta**. - The character of the shoreline around the Mississippi river delta complex varies considerably, dependent upon nearness to the major distributaries of the river. Today, the main channel of the river is building a large birdfoot delta out onto the continental shelf. At positions formerly occupied by the major distributaries, however, the abandoned delta lobe is subsiding and the shoreline is eroding at rates exceeding 10's of meters per year (Penland and Suter, 1983), and a system of barrier islands is forming. There are several abandoned lobes on the delta, each of which continues to erode. Therefore, whole environmental complexes come and go at the whim of the shifting distributaries of the delta.

> **Icy Bay, Alaska**. - Our field work in Alaska indicates that the shoreline west of Icy Bay is undergoing rapid erosion (over 1,000 m between 1900 and 1970; Hayes et al., 1973). This is presumably the result of the fact that a large glacier system, the terminus of which formerly occupied a position parallel to the present shoreline, had retreated over 40 km up inside the bay between 1900 and 1970. The whole character of the shoreline was altered dramatically as a result of this abrupt change in sediment supply. The termini of glaciers are a rich source of coastal sediments in southeastern Alaska.

River Deltas

The most striking manifestation of the impact of the zone of sediment supply upon shorelines is where a major river delta forms at a river mouth. This irregular progradation of the shoreline at the mouth of a sediment-laden stream may or may not conform to the "classic" shapes defined by such river deltas as the Nile and the Mississippi, depending on how the sediment mass is modified by marine processes. In order for the prograding delta form to have been developed on the modern ocean shoreline, the alluvial valley eroded during periods of lowered sea level during the ice ages must be aggraded to above sea level beyond the present shoreline. Where this has not happened, coastal water bodies referred to as estuaries, bays, or lagoons occupy the drowned river valleys. This type of valley flooding is primarily the result of insufficient sediment load of the river, but the process may be aided by tectonic downwarp or strong tidal flow that transports the river sediments offshore.

In their classic summary paper on marine deltas, Coleman and Wright (1975) discussed over 50 parameters that have an impact on river delta morphology. Factors such as characteristics of the drainage basin, river slope, tectonic setting, and coastal climate were acknowledged. Most present-day workers, however, following the original ideas of Price (1955) and Bernard (1965), try to simplify matters by focusing on three basic factors—sediment supply, wave energy, and tidal current energy—in their attempts to define the morphological character of deltas. The ratio of constructive (i.e., sediment supply) to destructive (i.e., waves and tidal currents) processes was used by Fisher et al. (1969) to classify deltas. Galloway (1975) placed this concept on a ternary diagram, with sediment supply, wave-energy flux, and tidal-energy flux comprising the three end members.

Galloway's (1975) classification of river deltas in the marine environment is given in Figure 1-4. River-dominated deltas are characterized by lobate protrusions into the offshore area, such as the modern "birdfoot" delta of the Mississippi River. At river mouths where the sediment output is overwhelmed by the hydrodynamic processes at the shoreline, entirely different delta configurations result. Tide-dominated deltas, such as the Colorado River and Ganges/Bramaputra River deltas, have a characteristic funnel shape, with multiple estuarine channels at the river mouths. Wave-dominated deltas, such as the Nile River and Rhone River deltas, have smooth, arcuate to cuspate, sandy outer margins. In some areas, particularly on young mountain range and arid shorelines, steep gradient streams build alluvial fans into coastal waters, creating another type of delta called a <u>fan delta</u>. The nearshore zones of these deltas are characteristically steep and the beaches are usually coarse-grained sand and gravel.

The zone where the river's waters and suspended sediment load enters the marine environment is characterized by complex flow and mixing patterns. Oil spilled into this zone is usually subject to mixing with the water mass and interaction with the suspended sediments (see discussion of Santa Barbara spill in Appendix A). An example of one of the many ways riverine and ocean waters mix at river mouths is given in Figure 1-5. The type of mixing illustrated in this diagram, usually occurs at a major river mouth in a microtidal, relatively low wave-energy setting (e.g., one of the distributary mouths of the Mississippi River). The term buoyant effluent is applied to this type of river outflow. Wright (1985; p. 28-29) described the process

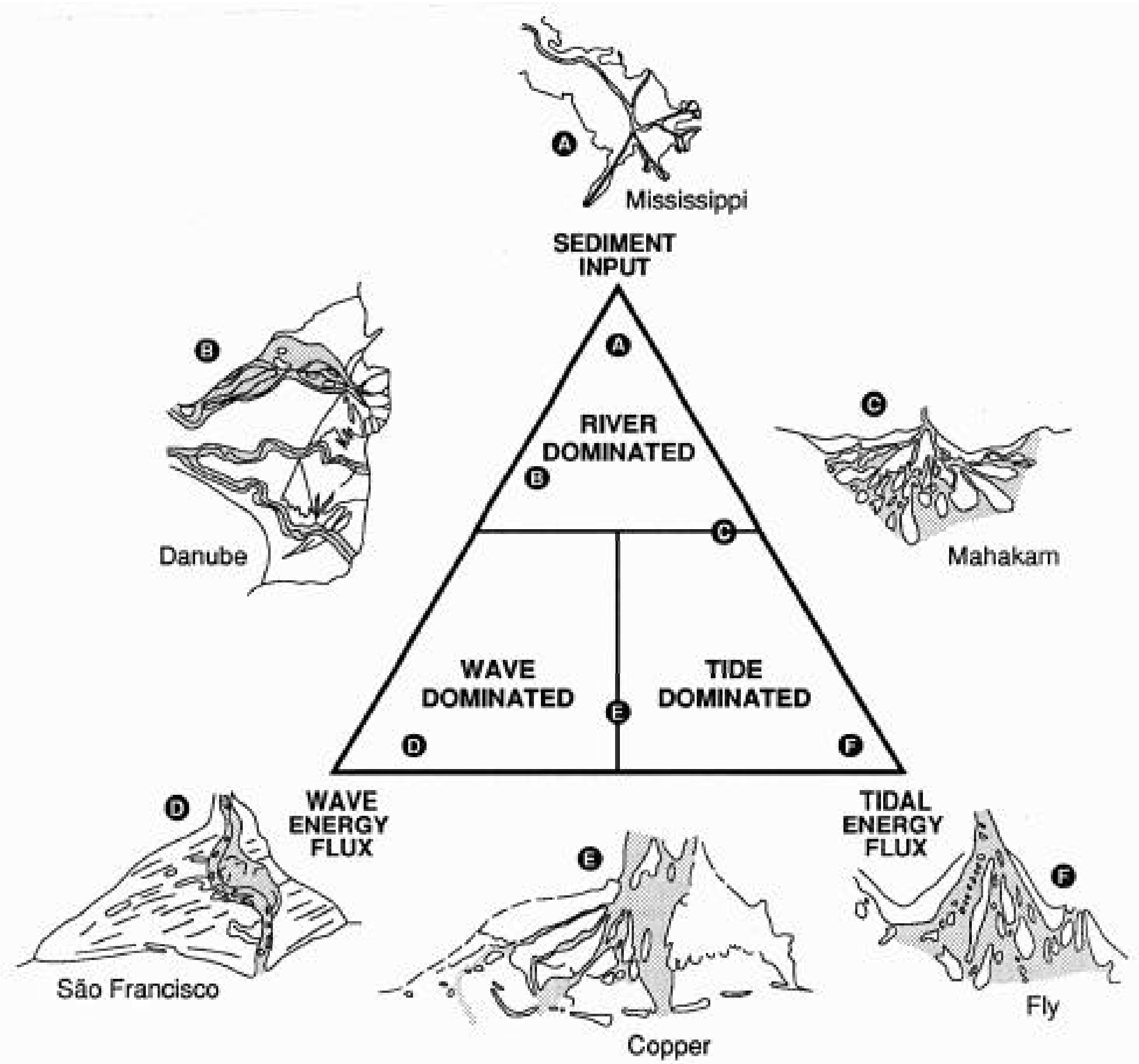

Figure 1-4. Classification of river deltas in the marine environment on the basis of sediment input, wave-energy flux, and tidal-energy flux. (From Galloway, 1975; Fig. 3.)

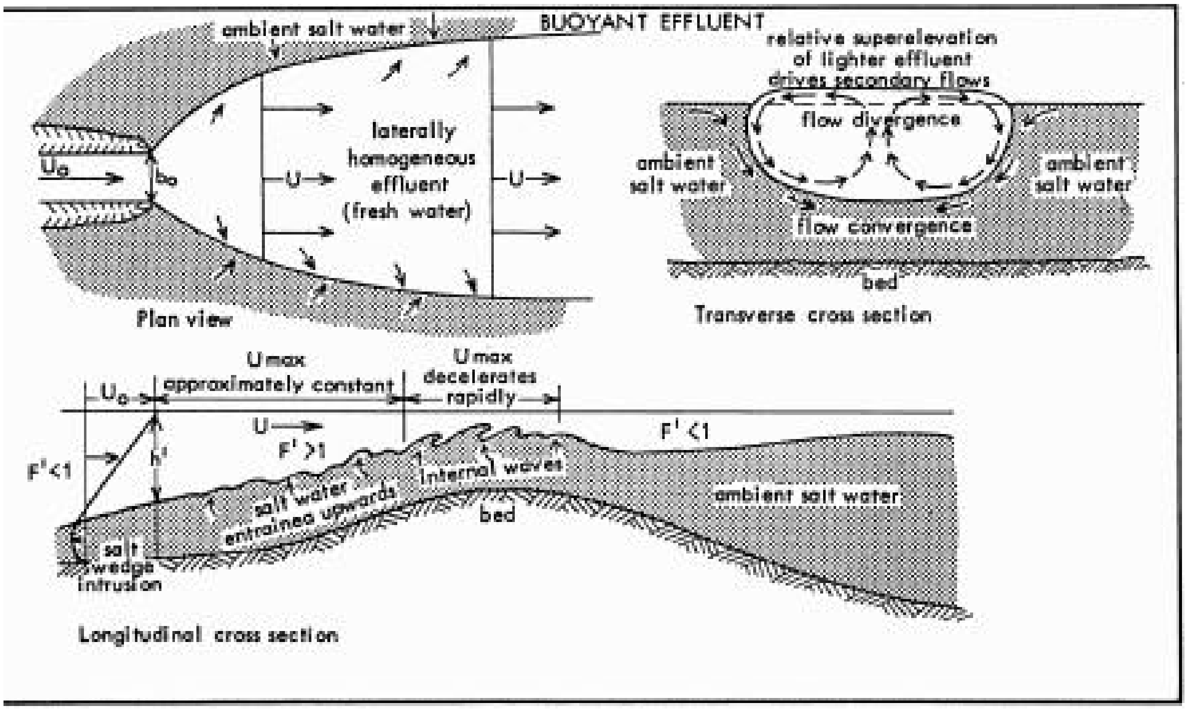

Figure 1-5. Spreading, mixing, deceleration, and secondary flow patterns of buoyant river-mouth effluents. Based on the Mississippi River mouth model. (From Wright, 1977a.)

as follows:

> "Visually dramatic and important features of buoyant effluents are pronounced frontal boundaries and related three-dimensional internal circulation patterns. ...Plume fronts are exceptionally sharp. ...Flow (V) divergence from the centerline of the buoyant effluent near the surface converges at the frontal boundaries with inward-directed saltwater transport from outside that plunges beneath the sloping pycnocline*. (Fig. 1-5) Flow in the lower part of the buoyant effluent is also directed inward. The net result of the combination of flow divergence near the surface and flow convergence near the pycnocline is the development of the dual helical cells illustrated qualitatively"... in Figure 1-5.

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*Boundary marking a sharp change in water density, as at a fresh-water/salt-water interface.

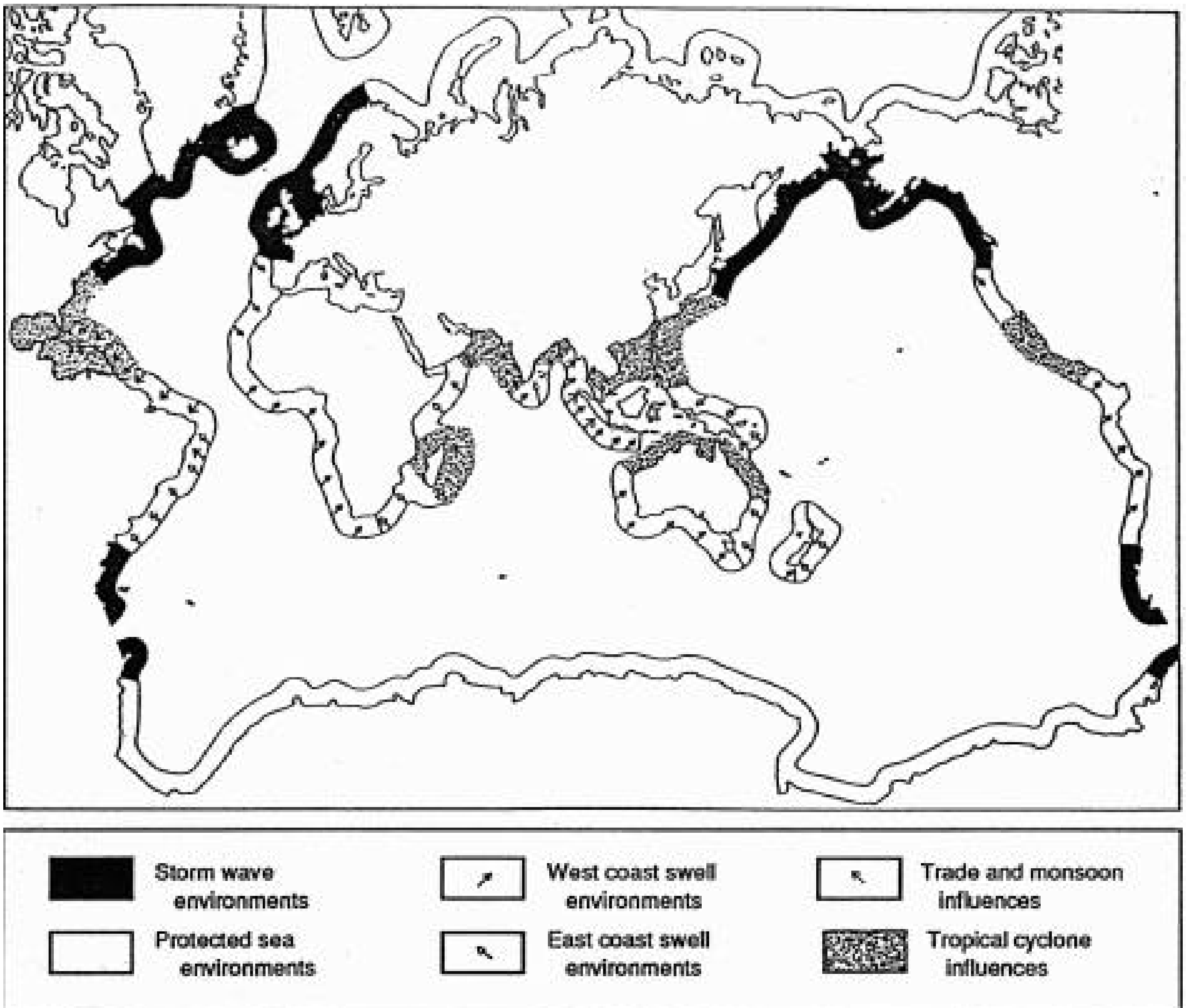

Figure 1-6. Major world wave environments. (From Davies, 1973; Fig. 27.)

Climate

Climate is an important factor in the shaping of coastal environments in that wave conditions, the occurrence of storms, and certain aspects of sediment production and supply can be related to it. Wave climate is controlled principally by global wind and storm patterns (see Fig. 1-6). Needless to say, the production of carbonate materials in the tropics and ice impingement on the shorelines of polar regions are also important climatic considerations. Vegetation type, also primarily related to climate, has an important effect on coastal sedimentation in some areas.

The role of climate in sediment production and supply for the continental shelf, and concurrently in the nearshore coastal zone, was investigated by Hayes (1967). It was found that:

1) Mud is most abundant off areas with high temperature and high rainfall (humid tropics).

2) Sand is everywhere abundant and increases to a maximum in intermediate zones of moderate temperature and rainfall and in arid areas of all, except extremely cold, temperatures.

3) Coral is most common off areas with high temperatures.

4) Gravel is most common off areas of low temperatures (subpolar and polar).

5) Rocky bottoms are generally more abundant in cold areas, but their distributions correlate strongly with tectonism of the adjacent land mass.

6) Shell distribution is not diagnostic with regard to climate.

Three primary climatic factors are thought to be responsible for these patterns. The type of weathering (chemical or mechanical) taking place in the source areas is of major importance in that it determines the availability of sediment types to streams (e.g., mud is most abundant off areas with intense chemical weathering). The presence or absence of major rivers (controlled by amount of precipitation) determines the volume of Holocene sediments being carried onto the shelf; hence sand is dominant on the inner shelves of arid areas due to the absence of river-transported mud. Deposition of coarse (gravel) sediments is virtually restricted to polar and subpolar areas, where they are deposited as the result of glaciation and ice-rafting. Other factors, such as source stream gradient and hydrodynamic energy, exert strong local influence, but are thought to be less important than the above climatic factors in determining world-wide, sediment distribution patterns.

Local Geological History and Sea-level Changes

The aspect of local geological history of shorelines related to plate tectonics was discussed above. When responding to an oil spill, the detailed local geological history of the spill site should be considered carefully. For example, areas that were glaciated during the Pleistocene, such as the coastlines of New England, Puget Sound, and the Great Lakes, have complex local configurations related to the passage of the ice. Shorelines produced by erosion of glacial till deposits differ markedly from flooded glacial scours, eroded outwash shorelines usually are associated with extensive sand-beach systems, and so on. Local faulting and earthquake history also leave an indelible mark on leading-edge coasts such as California and Alaska. The *Exxon Valdez* spill impacted some shorelines that had been uplifted (as much as 10 m) and some that had been downdropped (as much as 2 m) during the Good Friday earthquake of 1964. Several differences in spill behavior were noted on the opposite sides of the fault zone (Michel and Hayes, 1991).

Another important historical factor is the changes in sea level that have occurred relative to the last ice ages. It is generally conceded that sea-level dropped more than 100 m during the Wisconsin glaciation (Milliman and Emery, 1968). Beginning around 17,000 BP (Laville and Renault-Miskovsky, 1977), sea level probably rose rapidly to near its present level around 6,000 BP. A generalized sea-level curve for that time period is given in Figure 1-7. Details on the more minor variations in sea level that have occurred during the relative stillstand of the past 6,000 years have been greatly refined by excellent collaborative efforts by archeologists and geologists (e.g., DePratter and Howard, 1980; Colquhoun et al., 1981). The sea-level curve that has been derived for this time period on the South Carolina coast is given in Figure 1-8.

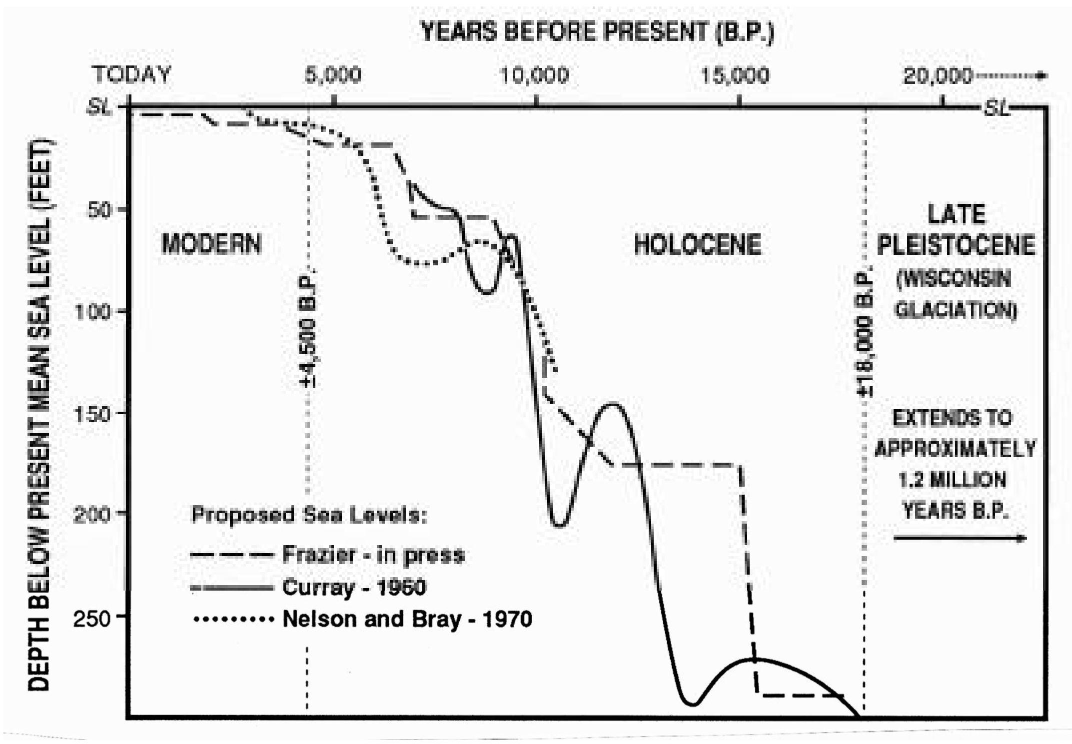

Figure 1-7. Proposed sea-level changes during the last 20,000 years for the Gulf Coast area. (From Fisher, et al., 1973; Fig. 5C.)

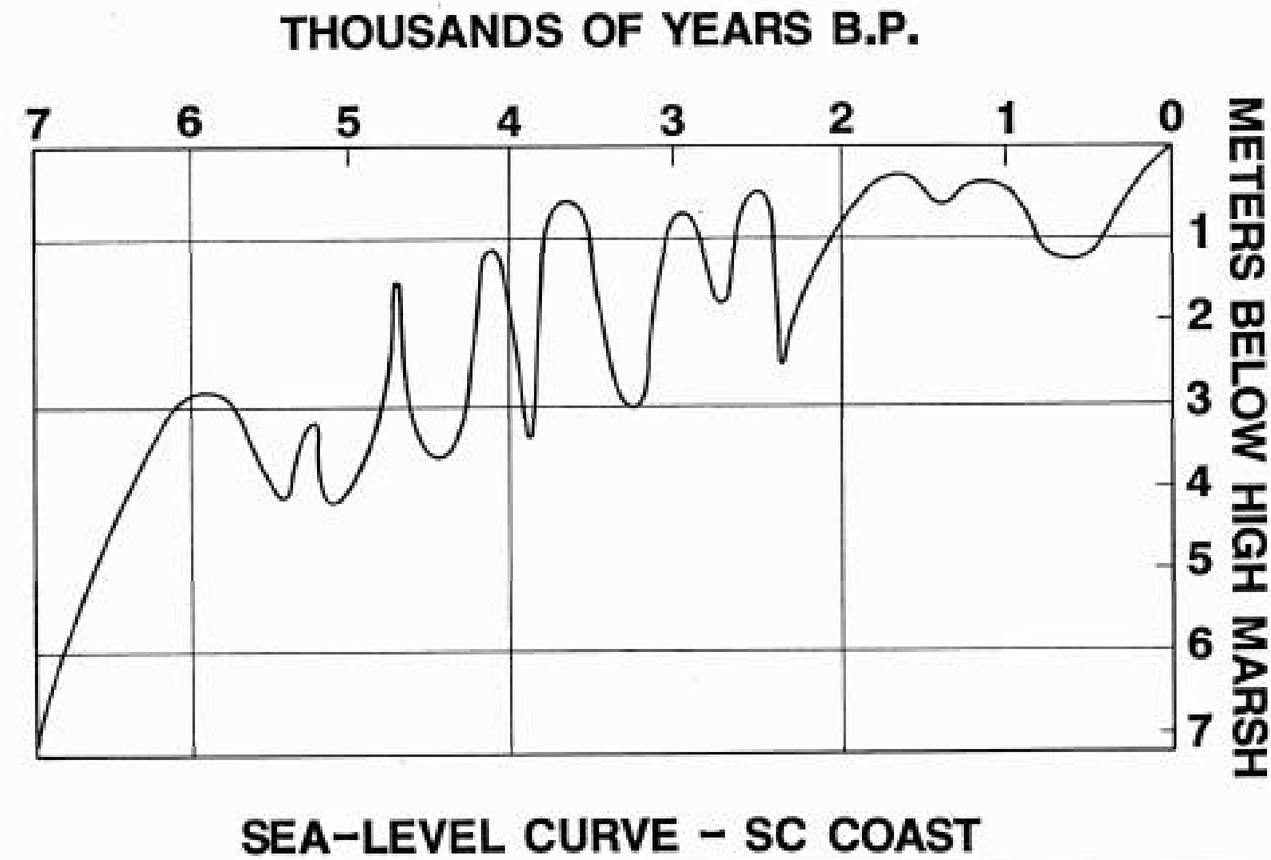

Figure 1-8. Changes in sea level on the South Carolina coast over the past 6,000 years, based on detailed, combined archeological and stratigraphical research. (Modified after Colquhoun et al., 1981 and Colquhoun and Brooks, 1986.)

Dynamic Coastal Processes

This section is a brief introduction to the important dynamic coastal processes that affect an oil spill site, including winds, waves, tides, and currents.

Winds

Probably the most important factor in dispersal of an oil spill is the effect of the wind. The importance of this factor was clearly illustrated during the spills of the *Amoco Cadiz*, *Florida*, *Bouchard No. 65*, and *Puerto Rican*, among others. During the *Amoco Cadiz* spill, consistent westerly winds over 20 km/hr accounted for a west-to-east dispersal of the oil and an initial uniform coating of the westward-facing shore during the first two weeks after the spill. The wind changed on 2 April and blew consistently from the northeast until 10 April. It was these northeast winds, aided by tidal currents, that dispersed the oil to the west and south, polluting previously unaffected eastward-facing coasts (Gundlach and Hayes, 1979).

Waves

Introduction

Waves are important at an oil spill site in that they:

1) May inhibit cleanup activities by creating rough seas.
2) Disrupt or inhibit booming activities.
3) Mix oil into the water column.
4) Erode the beach.
5) Cleanse beach sediments of oil.

The occurrence of wave environments on a worldwide basis is given in Figure 1-6. The highest wave energy is found in the storm-wave environments. High-to-medium wave energy is experienced on west coasts of continents in swell environments; wave energy varies from low to medium-high on east coasts of continents in swell environments. In major enclosed seas and along Arctic and Antarctic coasts, mean wave energy levels are low (Davies, 1973).

Most of the wave energy arriving at the shoreline is contained in <u>progressive waves</u> generated by winds blowing over the water. They are termed progressive waves because they move in the general direction the wind is blowing. These waves have two common forms: seas and swell.

Seas

Seas are highly irregular waves with pointed crests which are produced and influenced directly by the wind blowing over the water. They generally include a wide range of wave lengths and periods, making it difficult to describe the average wave. The height of waves at a given water depth depends on three factors: wind velocity, fetch (the waterway distance over which the wind blows), and wind duration (length of time a given wind velocity occurs). As each of these factors increases, wave heights increase.

Swell

When the wind stops blowing, seas become more rounded and smooth in appearance, approaching a sinusoidal shape. Such waves are called swell. Because the velocity depends on the period or wave length, swell waves tend to sort themselves out naturally at sea, traveling in groups with approximately equal velocity. Typically, the sea surface contains a complex pattern of locally generated seas interacting with swell from another part of the ocean.

Waves at the Shoreline

Seas and swell are transformed as they approach the coast because of the effect of friction as the depth of water decreases. If waves approach at an angle to the shore, they will bend (refract) toward the shore. Also, they will generally decrease in height because of shoaling and friction with the sea floor. Waves break when the depth of water is approximately equal to the height of the wave. Thus, a wave one meter high will usually break in about one meter of water.

Breaking Wave Types

There are three basic types of breakers which occur on beaches, mainly depending on beach slope (Fig. 1-9). Along gently sloping beaches, spilling waves are most common. These waves have a broad foam area at the wave crest as they

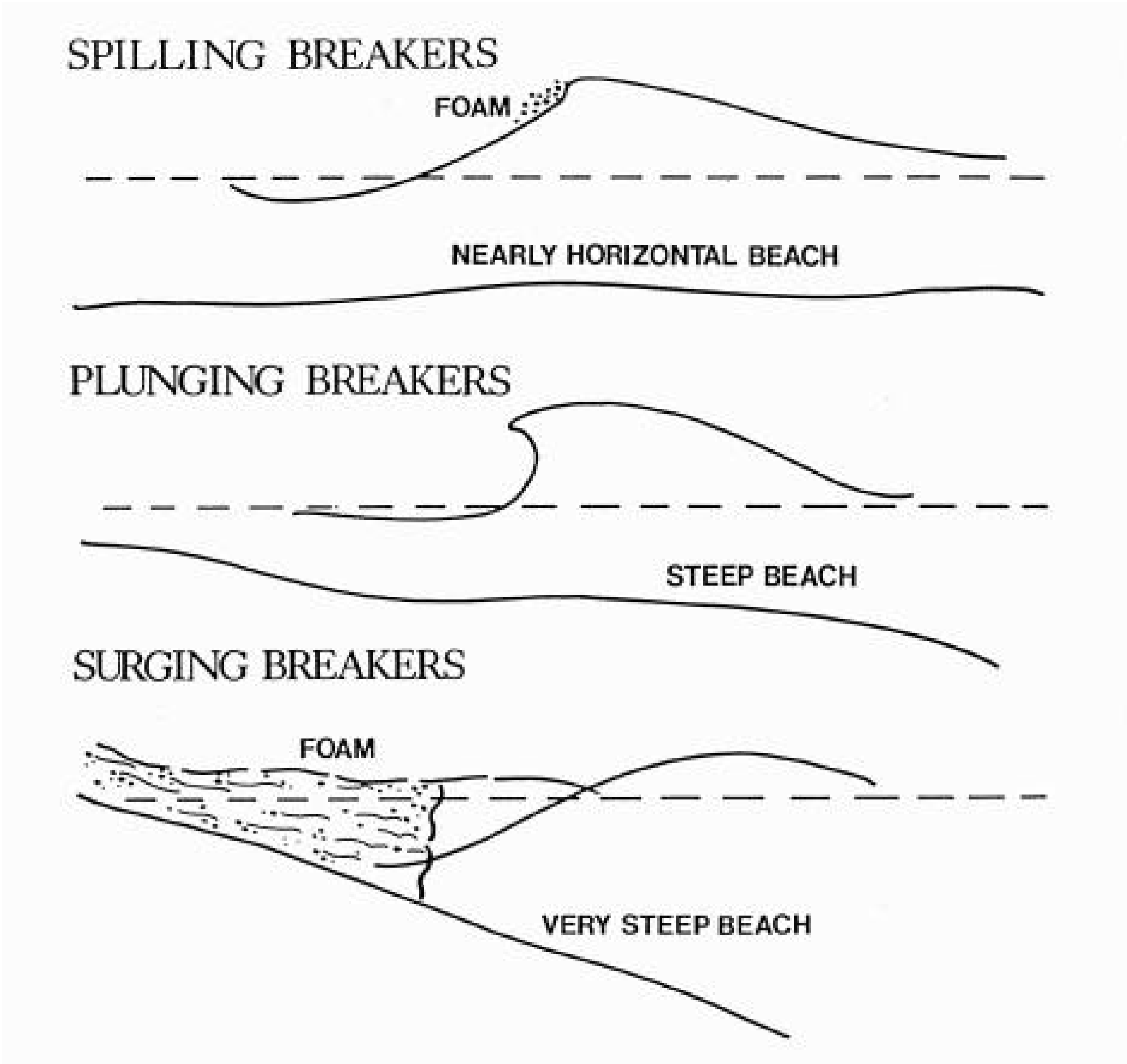

Figure 1-9. The three principal types of breaking waves that occur on the beach. (From Komar, 1976; Fig. 4-17.)

approach the beach, expending their energy over a relatively wide surf zone. As a rule, they tend to move sand onto the beach. <u>Plunging</u> waves occur as beach slope increases. They have curling breakers which entrain a vortex of air as they break. They are more violent than spilling waves and expend their energy rapidly over a narrow width of the surf zone. As a rule, they entrain more sediment than spilling waves and commonly tend to move beach sand offshore to the limit of the outer breaker line. Surging waves occur on steep slopes and are characterized by sloshing up and down the beach.

Wave Erosion

Steep, plunging waves generally cause shoreline erosion and retreat. A schematic representation of storm waves eroding a beach is given in Figure 1-10. Beaches typically erode during storms and recover to near-original profiles during intervening periods. In a few areas, such as the southern California coast and the monsoon-impacted coast of Oman, a seasonal beach cycle is present (winter erosion in California and summer erosion in Oman!).

Local Variations in Wave Energy

Wave energy is not distributed evenly along some shorelines. Usually, this is the result of wave refraction around an offshore island or rocks, over submerged bathymetric highs or lows, or as the result of a variable orientation of the coast.

The uneven distribution of wave energy along local shorelines (scale of a few kilometers) has been demonstrated in many areas. Two well-known examples, the coast of southern California and the Delmarva Peninsula, illustrate this principle. In southern California, submarine canyons occur close to the shoreline. Waves tend to refract away from the canyon openings, creating areas of decreased wave energy at the shoreline adjacent to the canyon heads. On the Delmarva Peninsula, submerged linear ridges project away from shore in a northeasterly direction. Waves passing over these ridges are focused by wave refraction near the points of intersection of the ridges with the shoreface. In both regions, beach erosion is most critical in areas where wave energy is focused by wave refraction.

Tides

The importance of tides in shaping coastal morphology is discussed above. Tides are also important at oil spills in that they: (1) generate currents that disperse the oil and (2) alternately expose and cover intertidal areas impacted by the oil.

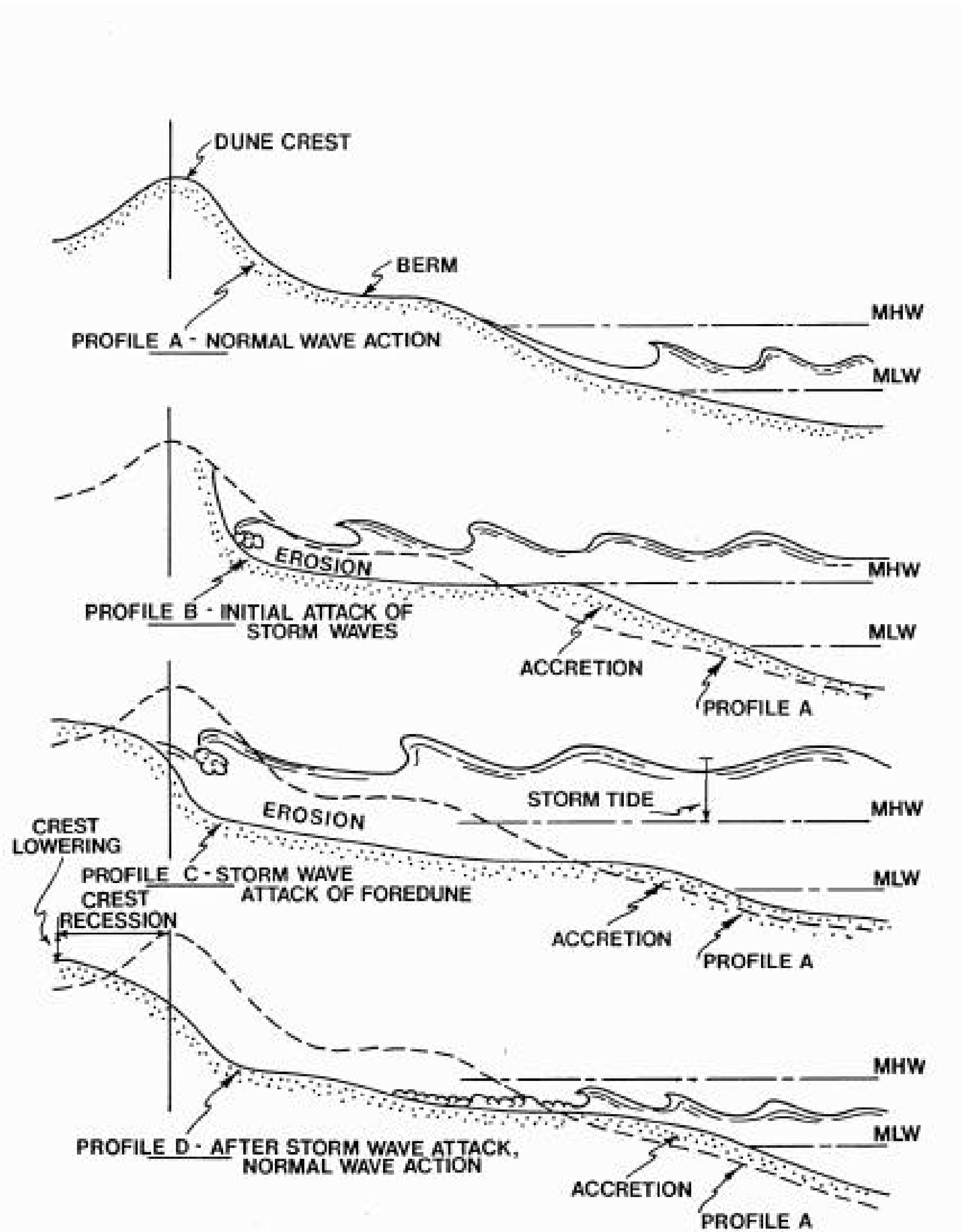

Figure 1-10. Schematic diagram of storm wave attack on beaches. (From CERC 1973; Fig. 1-7.)

The largest tides in the United States are experienced on the coast of Maine and in parts of Alaska (e.g., Cook Inlet and Bristol Bay). Small tides occur along the Gulf and Arctic coasts; medium tides occur along the rest of the U.S. shoreline.

The tides follow a cycle which is controlled by the position of the sun and moon relative to the earth. When the sun and moon are in syzygy (i.e., in line with each other), the tidal range is greatest (spring tides), and when they are in quadrative (i.e., at right angles to each other), the tidal range is least (neap tides). Spring and neap tides occur twice each lunar month.

The most severe erosion of the beach occurs at high tide. During spring tides, higher levels of the beach are exposed to wave action than during neaps, so erosion is at a maximum. This is an important consideration when predicting oil removal from sand beaches by natural processes.

Observations on the east coast of the U.S. by university researchers and the U.S. Army Corps of Engineers show that storms do their greatest damage when they cross the coast during a high spring tide. Observations on the southeastern U.S. coast show that the beach may be erosional during spring tides and depositional during neap tides under similar wave conditions. Erosion occurs at spring tide because (1) the dune ridge is exposed to wave action, and (2) the beach sediment is water-saturated because of the higher level of the sea.

It is important that careful attention be paid to the tides during a spill response, through repeated reference to the daily tidal curves, such as the ones shown in Figure 1-11. Reference must be made to the tidal data in order to: a) plan field surveys in order to utilize the times of maximum exposure of the intertidal zone; b) predict future impacts of exceptionally high or low tides; c) predict possible beach cycle changes; and d) anticipate changes in tidal current velocity and direction.

Currents

Importance at Oil Spills

Large oceanic current systems, such as the Gulf Stream, usually have little effect on coastal-zone oil spills. An exception occurred during the *Exxon Valdez* spill, when the Alaska coastal current carried oil from the spill hundreds of

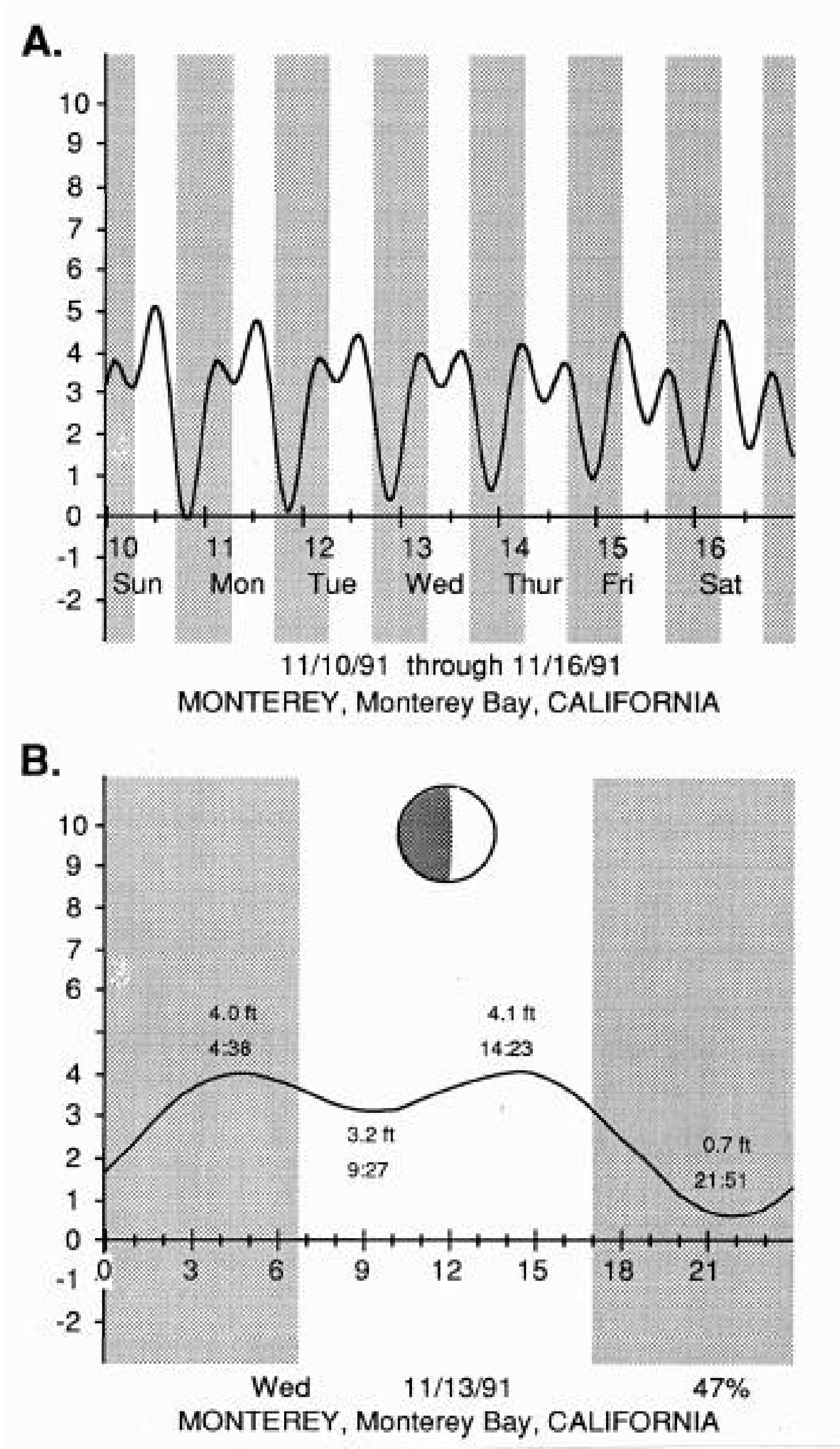

Figure 1-11. Tidal curves for the Monterey Bay, California area. A) The curve for a full week. Note the strong diurnal inequality. B) Curve for a 24-hour period.

kilometers along the coast. The current systems which are usually most important during spills are those induced locally by rivers, tides, winds, and waves.

River-induced currents are almost entirely confined to deltaic and estuarine situations and vary geographically with factors affecting the amount and seasonality of discharge (Davies, 1973; p. 52). During periods of high runoff, these currents would generally tend to keep the oil offshore, but the potential for mixing of oil into the water column should always be considered (e.g., see Fig. 1-5).

Tide-induced currents vary with tidal type and range, tending to be most powerful with semidiurnal tides of large range and least powerful with diurnal tides of small range. Further details were given by Davies (1973; p. 53).

> "Although tidal currents are reversing, inequalities between flood and ebb streams may often be significant in terms of net transport, and on coasts with mixed tides, the normal sequence of highs and lows may be of especial importance in producing such inequalities. Thus, if the sequence is low low water, low high water, high low water, high high water, the two flood currents are essentially equal in magnitude and duration, but the two ebb currents are unequal so that velocities in the great ebb between high high water and low low water may be much greater than at either of the flood stages. Conversely, a sequence of high high, high low, low high, low low gives one exceptionally strong flood current between low low and high high water.
>
> In coastal inlets, the size, and particularly the length, of the inlet may affect the phase relationship between tidal stage and current velocities. Normally, the highest velocities occur at mid-tide, but in long estuaries, there may be considerable divergence so that, near the mouth, low tide may be associated with the fastest ebb and high tide with the fastest flood. This may have a morphologic effect by influencing the height at which strongest currents operate."

In short, these currents can be very complex, thus site specific data are usually required.

Wind-induced currents are highly variable; thus, a constant monitoring of wind conditions at the spill site is necessary for prediction of oil-slick motion.

Wave-induced currents are produced by wave setup along the shore and are basically divisible into longshore currents, resulting from oblique wave approach and running more or less parallel to the shore in the surf zone, and rip currents that move outward from the shore. These types of currents are important in transporting oil and oiled sediments once oil from the spill impacts the beach where it may be either resuspended into the surf zone or become incorporated as part of the sediment mass.

All of the above types of currents combine and interact to produce very complicated current systems in the nearshore zone, as is illustrated for the La Jolla, California area in Figure 1-12. Detailed site-specific data and continued monitoring of wind and tidal conditions are almost always required to accurately predict oil trajectories in the nearshore zone.

Importance to Coastal Sedimentation

Of the different types of currents present, wave-generated currents have the most important influence on open coast beaches. Tidal currents are important in modifying sediment transport near inlets, but have little effect on uninterrupted straight shorelines, except in areas with very large tidal ranges (greater than 4 m). Ocean currents only rarely affect nearshore sediment transport. A notable exception is the Guyana Current, a branch of the North Equatorial Current, which moves large quantities of fine-grained sediment discharged from the Amazon River along the shoreline of northeastern South America (Fig. 1-13).

Wave-generated currents include longshore currents and rip currents. Longshore currents are discussed in Chapter 3. Rip currents flow from the beach seaward and are generally part of a well-defined nearshore cell circulation such as is illustrated in Figure 1-14. The most commonly held theory for the origin of rip currents is that they result from interactions between incoming waves and edge waves trapped within the nearshore system (Komar, 1976). Edge waves are free-wave motions introduced by a coast in its interaction with surges or lower-period oscillations (Bowen and Inman, 1971). They are generally standing waves with crests normal to the shoreline and wave lengths from crest to crest parallel to the shoreline (Komar, 1976; p. 176). Bowen and Inman (1969) demonstrated that longshore variations in wave setup caused by periodic longshore variation in wave height generate lateral flow, with rip currents flowing seaward at the positions of lowest wave heights.

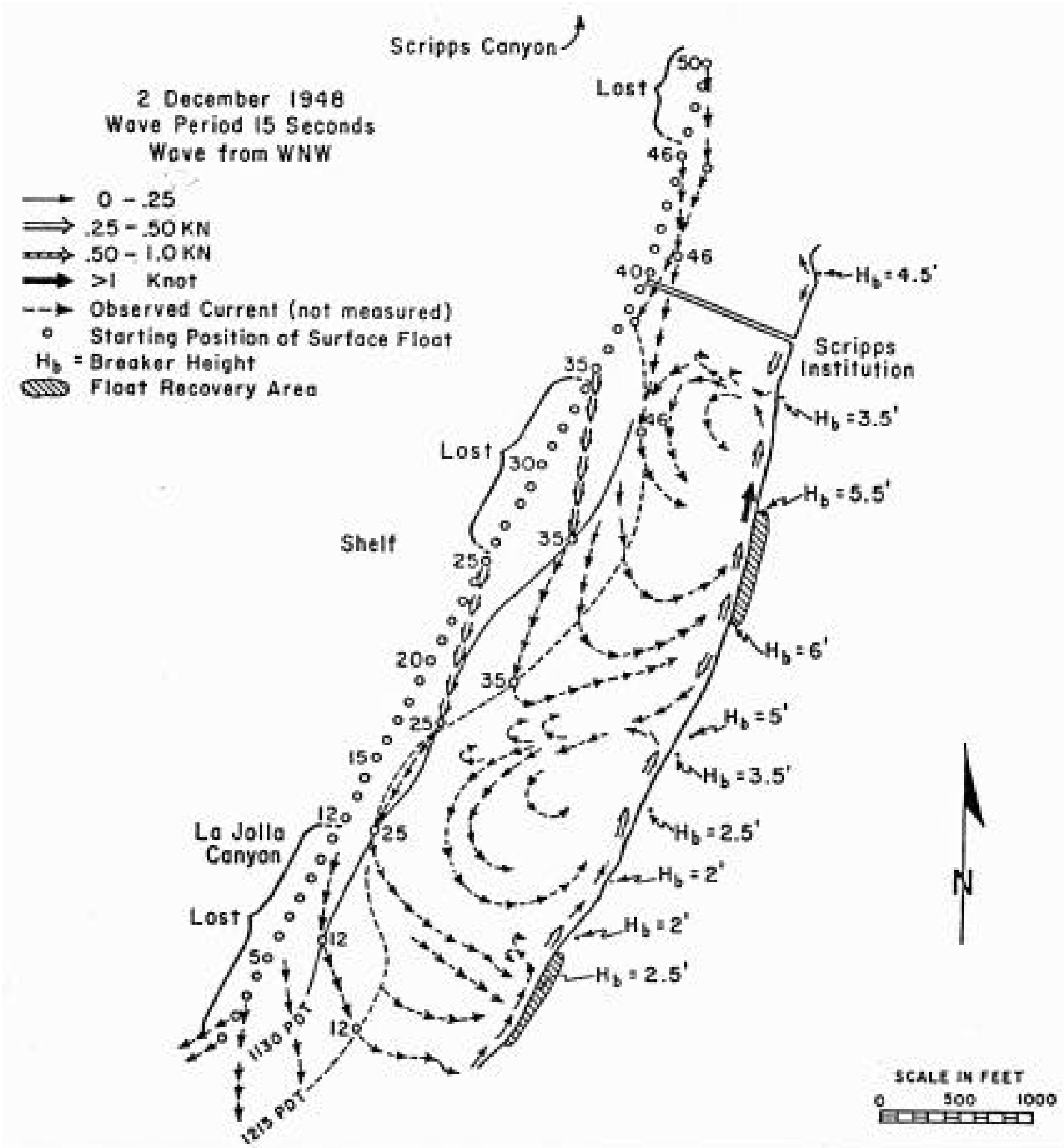

Figure 1-12. Nearshore current sytem near La Jolla Canyon, California on 2 December 1948. (From Shepard and Inman, 1950.)

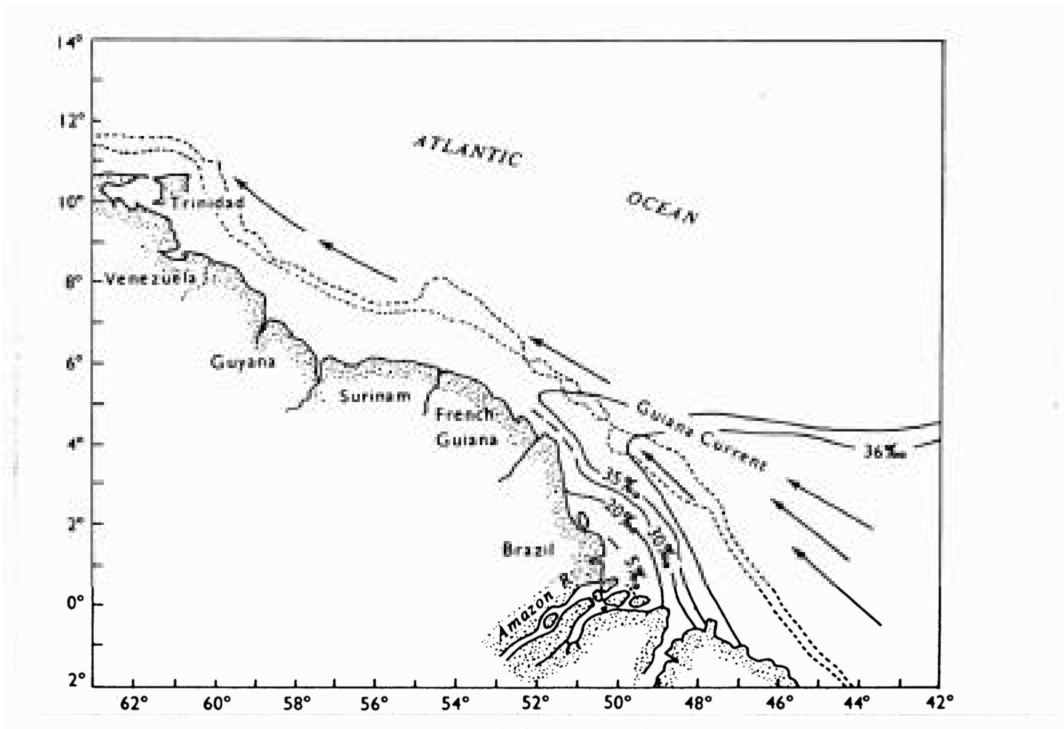

Figure 1-13. Surface currents over the Amazon Delta front. (Based on data of Gibbs, 1980; from Wright, 1985; Fig. 1-28.)

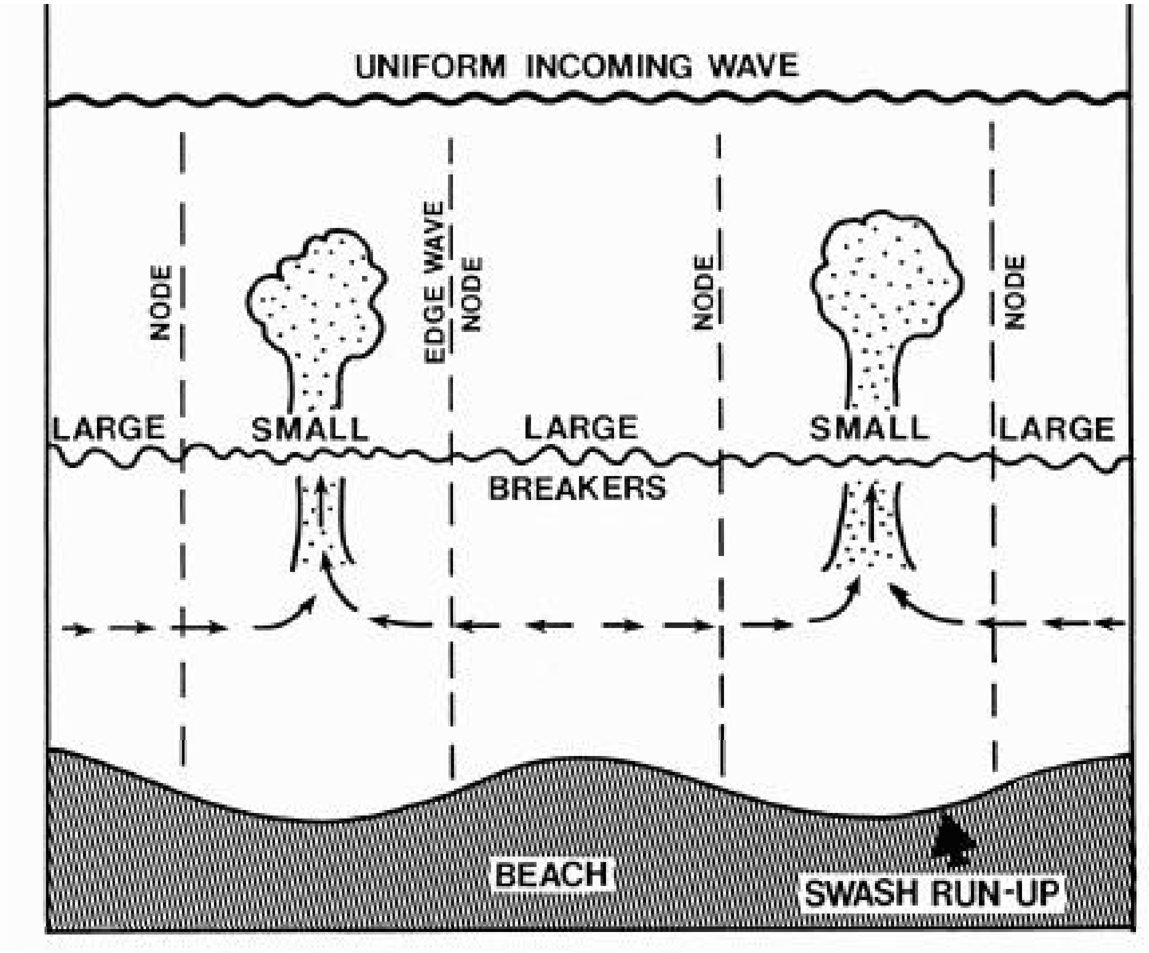

Figure 1-14. Illustration of nearshore rip currents. Note the positioning of the currents where the breaker height is smallest—that is, where edge waves and incoming waves are 180 degress out of phase. (From Komar, 1976; Fig. 7-8.)

Wave heights are least where the edge wave and incoming wave are 180 degrees out of phase (see Fig. I-14; from Komar, 1976). Rip currents carry sediments off the beach during erosional events. The authors have observed rip currents carrying significant quantities of oil offshore during a spill at Cape Hatteras, North Carolina and at the *Peck Slip* spill in Puerto Rico.

Coastal Storms

The most dramatic changes of shorelines occur during major storms, which usually result from the passage of tropical or extratropical cyclones. Much of the eastern and southern shoreline of the United States is affected by a tropical cyclone, or hurricane, every few years (Fig. 1-15). Most of these storms result in extensive coastal flooding, severe beach erosion, and loss of property and lives. A tropical cyclone that occurred on the Texas coast in September 1979 removed much of the oil that had accumulated on the beach as a result of the *Ixtoc 1* spill (discussed further in Chapter 3).

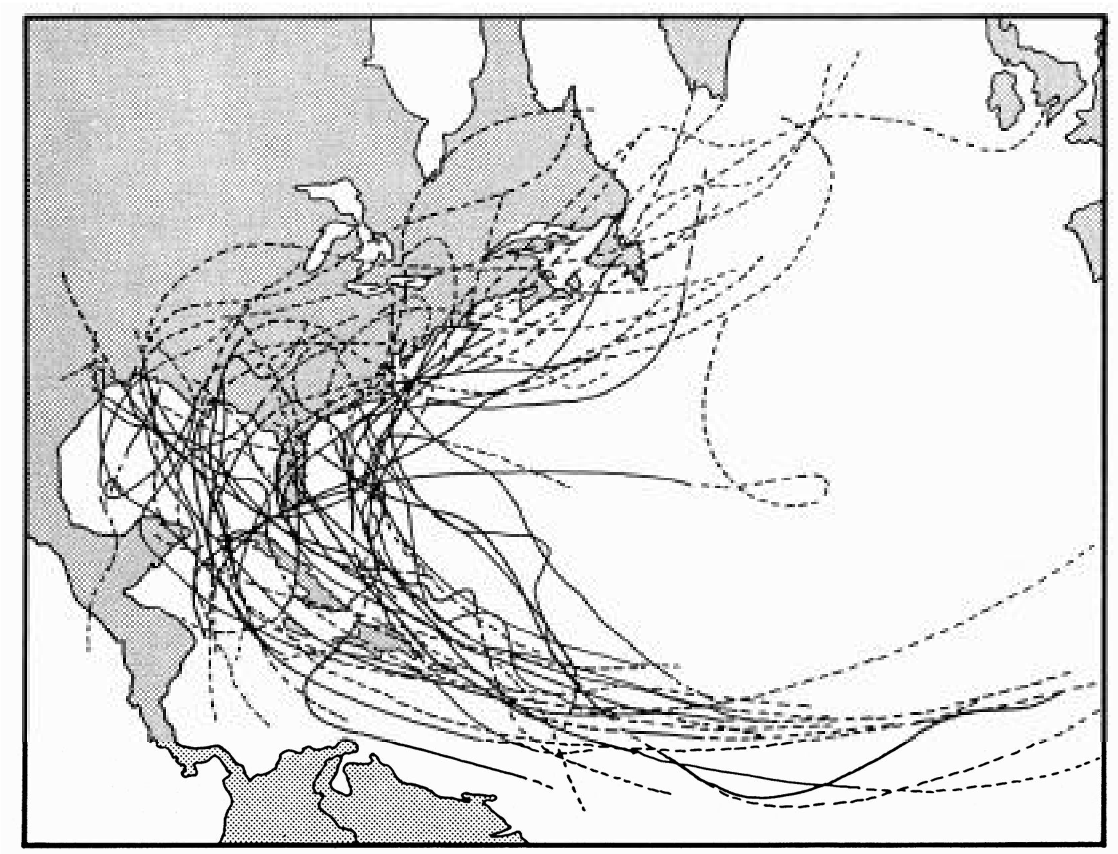

Figure 1-15. Computer plot showing the tracks of a selected number of Atlantic tropical cyclones, 1886 through 1969. (From Neumann and Hill, 1976.)

Extratropical cyclones are the dominant force in initiating beach cycles on the east coast of North America (discussed in Chapter 3). The effectiveness of these storms, which occur several times a year, is determined by: (1) size of storm; (2) speed of storm movement; (3) tidal phase and stage; (4) storm path; and (5) time interval between storms (Hayes and Boothroyd, 1969). Both hurricanes and extratropical cyclones breach barrier islands and create new tidal inlets, a process of concern during a spill response because the new inlets provide an avenue for oil from an offshore spill to reach sensitive lagoonal or estuarine habitats.

The Three-Dimensional Beach

The beach is a three-dimensional body of sediment made from material carried to the site by wave-generated currents which flow both parallel and perpendicular to the shore. On many sandy shorelines, a type of rhythmic beach topography (Homma and Sonu, 1962) develops. This topography has been described for the coasts of the Netherlands (Bruun, 1954), North Carolina (Dolan, 1971), the Great Lakes (Evans, 1939), Cape Cod (Goldsmith and Colonell, 1970), and several other localities. Sonu (1968), who termed the features "cusp-type sand waves", discussed them in detail. He stated (p. 383) that Evans (1939) was probably the first to describe their formation. The total system of rhythmic topography migrates parallel with the shore in the direction of longshore drift at different rates, depending upon the size of the features, the local wave climate, and probably the grain size of the sediment. In the process of formation of rhythmic topography, depositional berms assume cusp-like shapes; however, these cuspate forms are considerably larger than normal beach cusps. The wave lengths of most of the cusp-type sand waves at Cape Hatteras, North Carolina, ranged between 500 and 600 m, and they migrated at rates averaging between 100 and 200 m per month (Dolan, 1971; p. 177). The most important implication of the recognition of the abundance of rhythmic topography, according to Dolan (1971; p. 178), is the fact that "sand beaches cannot be considered in terms of stationary straight lines or simple angles, but must be treated as nonstationary sinuous forms." A sketch of the type of rhythmic topography described by Sonu (1968; 1973) is given in Figure 1-16.

Studies in recent years on the microtidal, sandy beaches of the swell-dominated southeastern coast of Australia have provided a more detailed accounting of the three-dimensional variability of high-energy beaches (Short, 1978; Wright et al., 1979).

The combined work of Short, Wright, and their colleagues on the southeastern coast of Australia gave birth to the concept of <u>morphodynamics</u>, which is defined as the "combination of beach-surfzone morphology and wave-current dynamics" (Short, 1979; p. 553). Short (1979; p. 567) stated that "breaker wave power provides energy to

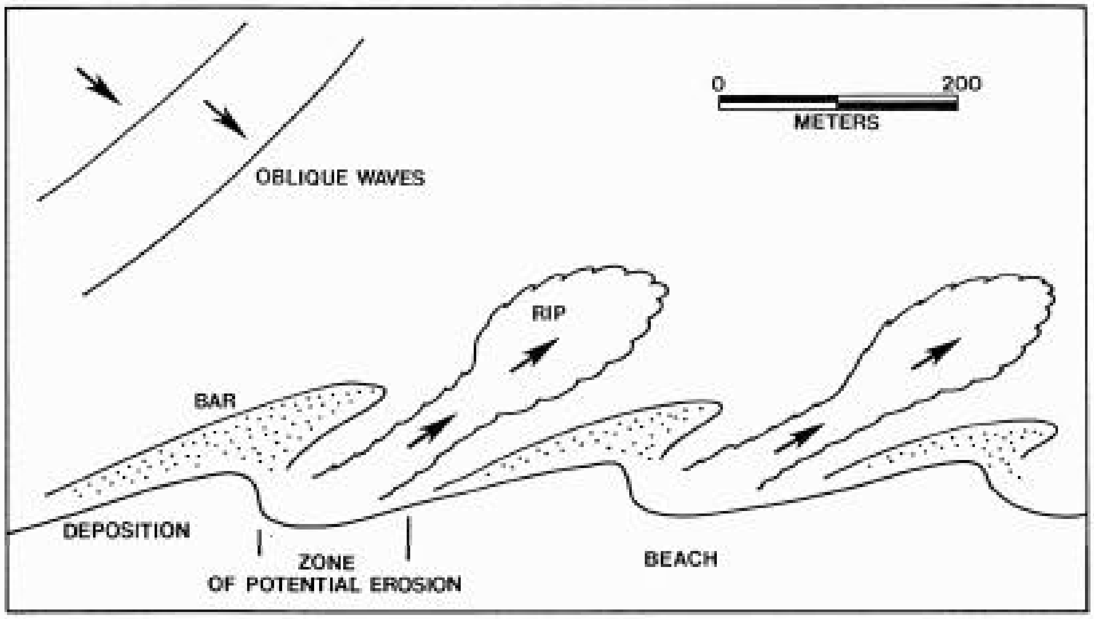

Figure 1-16. Rhythmic beach topography as described by Sonu (1973). The shoreline bulges move in the direction of longshore sediment transport at rates of up to hundreds of meters per year.

move a beach through various beach stages". Wright et al. (1979) placed emphasis on the reflective and dissipative nature of beaches, based on extensive field measurements of surf and inshore current spectra and inshore circulation patterns.

According to Wright et al. (1979; p. 105), reflective sandy beaches are characterized by steep, linear beach faces, well-developed berms and beach cusps, and surging breakers with high runup and minimum setup; rip cells and associated three-dimensional inshore topography are absent. Dissipative sandy beaches are typically found on open coasts and are characterized by concave-upward nearshore profiles and wide, flat surf zones which may contain multiple bars. Waves break tens of meters seaward of the beach and dissipate much of their energy before reaching it. Typical reflective and dissipative beach profiles are shown in Figure 1-17.

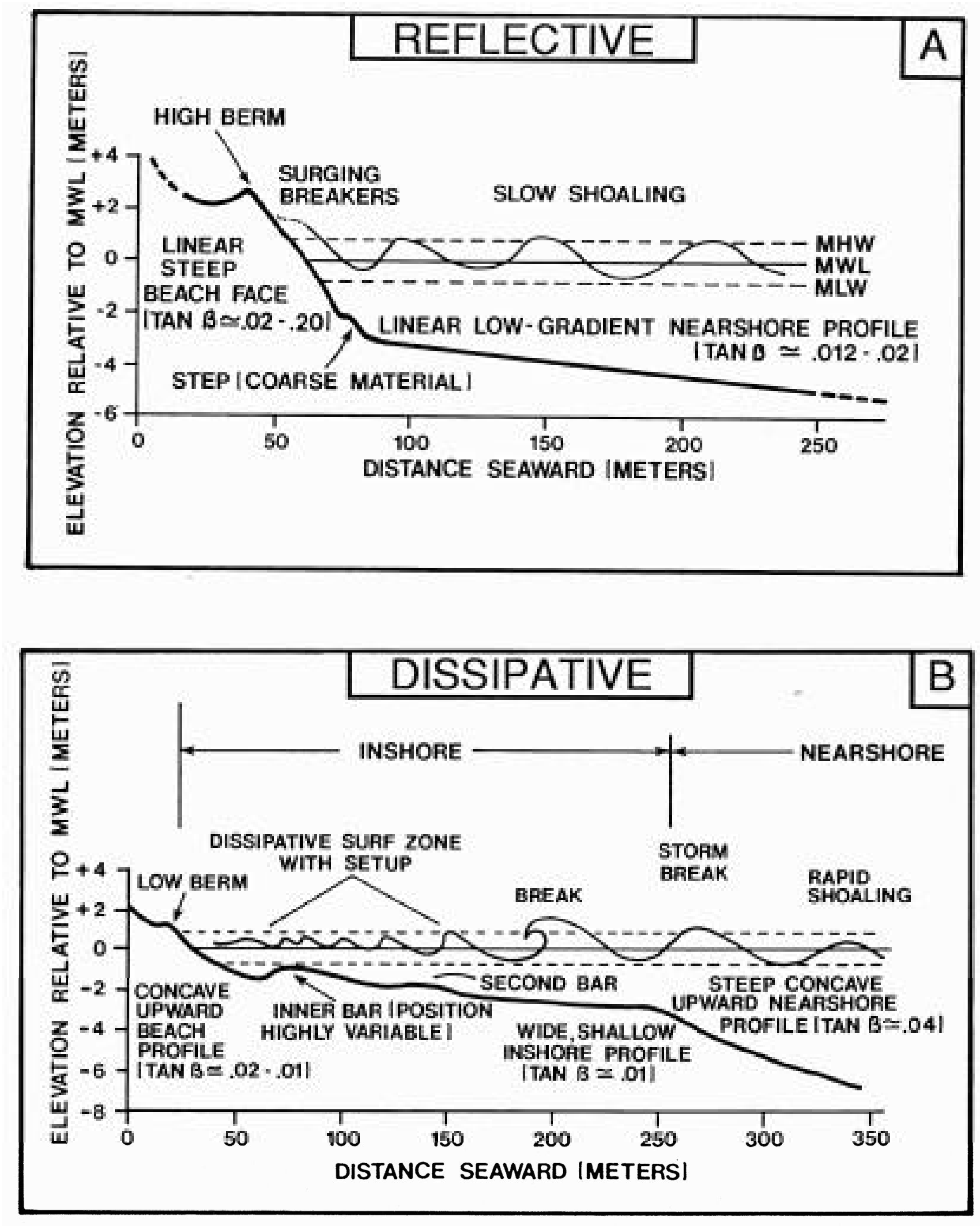

Figure 1-17. Typical cross-sectional profiles of reflective (A) and dissipative (B) sandy beach profiles. (From Wright et al., 1979; Figs. 3 and 6.)

Coastal Sediments

Introduction

The characteristics of the coastal sediments at the spill site are of primary importance. All cleanup programs must be attuned to the nature of the oil/sediment interactions. For example, oil does not penetrate fine-grained sand beaches but may percolate down to several tens of centimeters in gravel beaches.

Sediment Texture

Coastal sediments are classified according to the dominant size of the individual clasts into three general categories: 1) gravel, mean size greater than 2.0 mm; 2) sand, mean size between 0.0625 and 2.0 mm; and 3) mud, mean size less than 0.0625 mm. As shown in Figure 1-18, the general classes may be subdivided further.

The Wentworth (1922) classification of grain size is the one used most widely by engineers and geologists. It is a logarithmic scale in that each class limit is twice as large as the next smaller class limit (Fig. 1-18). The property of having class limits so defined led Krumbein (1936) to propose a phi unit scale based on the following definition: phi units (F) = $-\log_2$ (diameter in mm). The phi scale of Krumbein, which is shown in Figure 1-18, is used to calculate statistical parameters of sediment grain-size populations.

The grain size of mud is measured by pipette analysis and that of sand with sieves or a settling tube. Gravel sizes are determined by measurements of the long, intermediate, and short axes of individual clasts. Ratios of the different clasts of gravel occurring on a beach (i.e., granule, pebble, cobble, boulder) can be estimated visually by comparing the beach sediment with the chart shown in Figure 3-14.

Composition of Beach Sediments

Sediments on beaches range from coarse-grained fragments of rocks, usually derived from local rock outcrops, to fine-grained sand, derived from 10’s to hundreds of miles away. Quartz sand is the most common constituent of beach sediments because of its relative abundance in the earth’s crust, as well as its chemical stability and resistance to abrasion. Carbonate sand beaches are common in tropical regions.

A summary of the generalized global occurrence of beach sediment, with regard to its composition, is given in Table 1-1.

General Class	Wentworth Scale (Size Description)		Phi Units ø*	Grain Diameter d (mm)
GRAVEL	Boulder			
			−8	256
	Cobble			
			−6	64.0
	Pebble			
			−2	4.0
	Granule			
			−1	2.0
SAND	Sand	Very Coarse		
			0	1.0
		Coarse		
			1	0.5
		Medium		
			2	0.25
		Fine		
			3	0.125
		Very Fine		
			4	0.0625
MUD	Silt			
			8	0.00391
	Clay			
			12	0.00024
	Colloid			

Figure 1-18. Grain-size scale. (From CERC, 1973; Fig. 4-7.) Phi unit scale is indicated by writing ø or phi after the numerical value.

Table 1-1. Generalized global occurrence of beach sediment.

Tropical regions	Carbonate sand composed of coral and algal fragments, shell, and carbonate precipitates abundant; quartz and rock fragments common in sand, especially in areas of eroding bedrock and near river mouths
Temperate regions	Quartz sand dominant; rock fragments and feldspar abundant in sand near river mouths and along coasts with eroding bedrock
Subpolar and polar regions	Gravel beaches of highly variable composition abundant; pure sand present on long, exposed beaches; quartz and rock fragments common in sand
Oceanic islands	Volcanic sands (normally black in color) and carbonate sands common

Estuaries—Bays—Lagoons

Introduction

Semi-enclosed water bodies of relatively small dimensions that separate the land from the sea are termed estuaries, bays, or lagoons, depending upon configuration and their hydrographic characteristics. On coastal plain shorelines, many of these water bodies are sheltered behind barrier islands. Drowned river valleys, such as Chesapeake Bay and Delaware Bay, are also common. The classic definition of the term “estuary” was given by Pritchard (1967) as follows:

> “a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted by fresh water derived from land drainage”.

Patterns of sedimentation in the “classic” estuaries are very complex, owing to the interaction of tidal currents, waves, and biogenic processes. Coarsest sediments occur in the inlets, on the tidal deltas, and in the larger tidal channels, whereas finest sediments occur on the tidal flats and in the salt marshes.

Relationship to Tidal Range

Hayes (1975) pointed out that the distribution of coastal habitats and sediments within semi-enclosed coastal water bodies is controlled largely by the tides. The coastal water bodies were grouped and discussed, as follows, into the three major tidal classes. General models for the three classes are given in Figure 1-19.

Microtidal Systems

The processes that dominate in microtidal systems are created by wind and wave effects. Wind tides are commonly generated and extensive wind-tidal flats may develop. The wave-formed features include aligned bay beaches, recurved spits, and cuspate spits. Tidal currents generated by the astronomical tide are important only at the inlet throat. In some instances, however, large intertidal shoals (flood-tidal deltas) can develop on the landward sides of the inlets.

Mesotidal Systems

These systems differ from those of microtidal areas in that sediments deposited by tidal currents begin to predominate. The barrier islands themselves are short and stubby, and the tidal deltas are large and conspicuous. Meandering tidal channels occur behind the barriers; point-bar deposits containing bedforms generated by tidal currents usually predominate in these channels. The principal sand deposits in mesotidal estuaries are the tidal deltas. Hayes (1969) proposed the following terminology for the two major sand deposits associated with tidal inlets: (a) <u>ebb-tidal delta</u>—sediment accumulation seaward of a tidal inlet, deposited primarily by ebb-tidal currents and modified by waves, and (b) <u>flood-tidal delta</u>—sediment accumulation formed on the landward side of an inlet by flood-tidal currents. The general morphological model for a tidal inlet is given in Figure 1-20.

Macrotidal Systems

The most prominent feature of this type of coastal water body is the overwhelming dominance of tidal currents. Such systems are usually broadmouthed and funnel-shaped. Sand deposition is normally concentrated in the center of the water body, away from shore, which is usually dominated by broad, muddy tidal flats. The sand bodies are long linear features oriented parallel with the tidal currents.

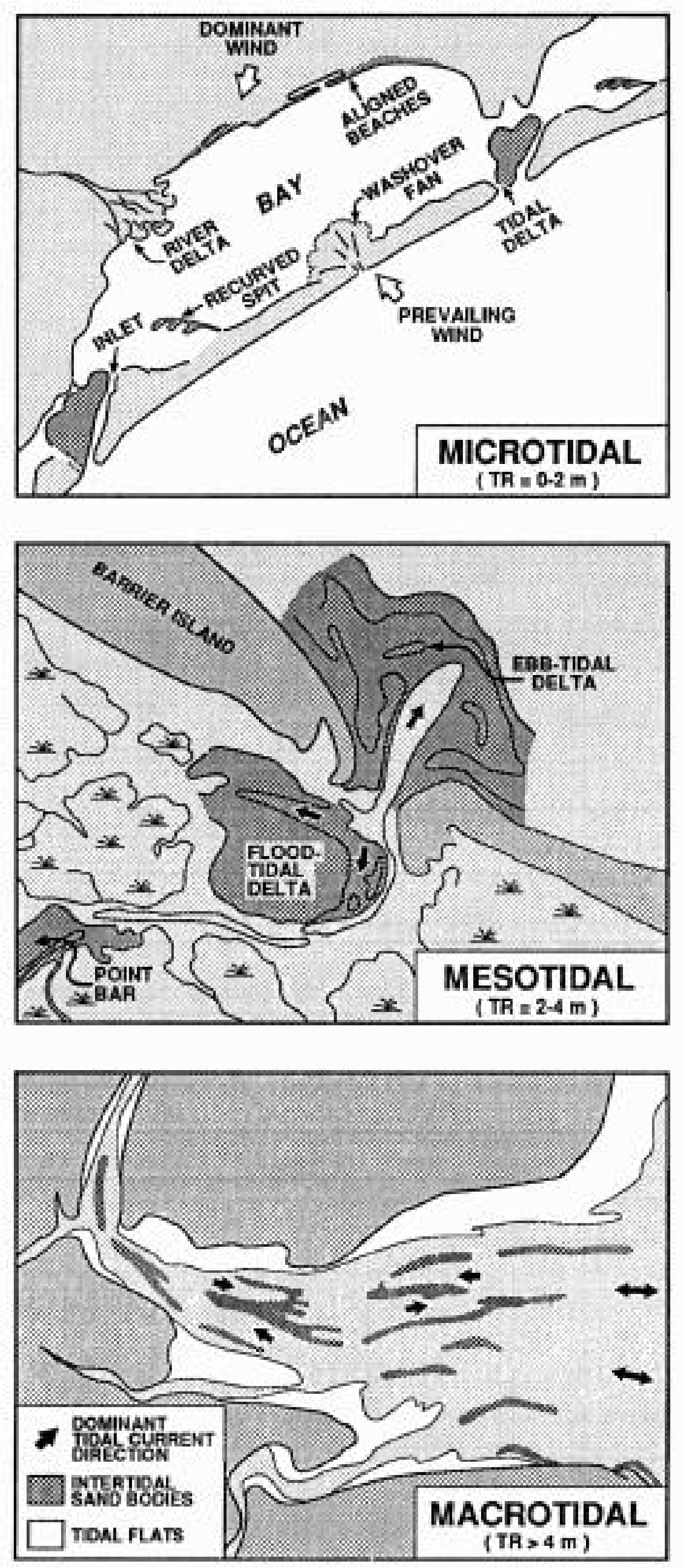

Figure 1-19. Variations of coastal estuaries, bays, and lagoons in response to differences in the tides. (After Hayes, 1975; TR = tidal range.)

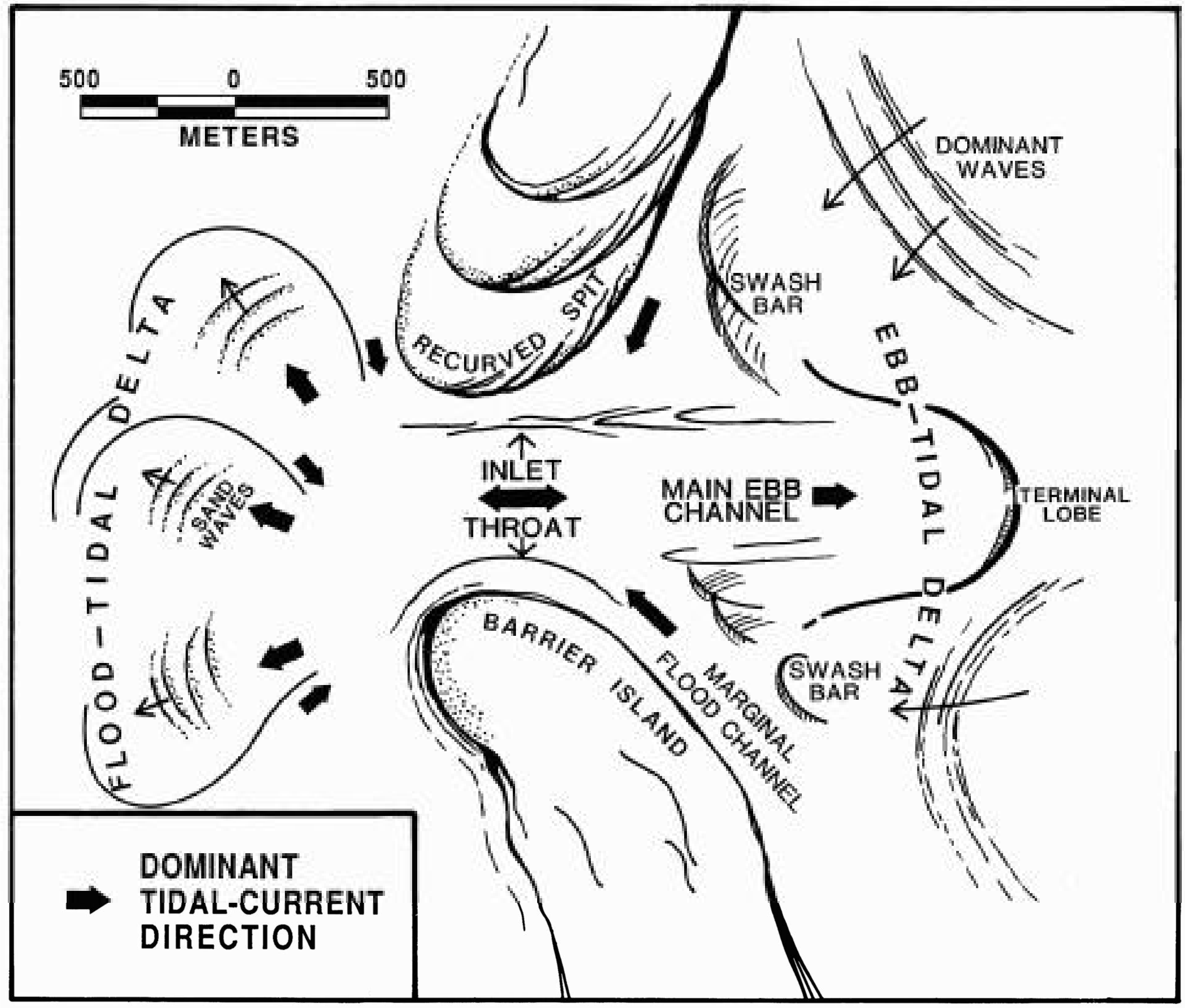

Figure 1-20. General model showing the morphological components of a tidal inlet.

Water Circulation and Mixing

As can be seen from the plan-view map of a group of Georgia estuaries (mesotidal) in Figure 1-21 and a hypothetical cross-section of a Chesapeake Bay-type estuary in Figure 1-22, oil spilled in either the entrance or the interior of a major estuary will be subjected to complex circulation and mixing patterns. Water circulation at the entrances to the Georgia estuaries is controlled by ebb- and flood-tidal currents, which are commonly both horizontally and vertically segregated, and complex wave-generated currents created by wave-refraction around the shoals at the estuary entrances (ebb-tidal deltas). The circulation pattern of both water masses and their suspended sediment loads inside major estuaries, which is illustrated in Figure 1-22, makes estuaries very effective traps for fine-grained, suspended sediments. The flocculation and entrapment of the sediments occurs predominantly in the zone of mixing between the fresh and salt water. This zone is sometimes referred to as the "turbidity maximum", because of the overabundance of suspended sediments in that zone. Oil from the *Amoco Cadiz* spill was entrapped in the bottom sediments of some of the estuaries in Brittany, France probably as a result of getting caught up in this type of circulation pattern.

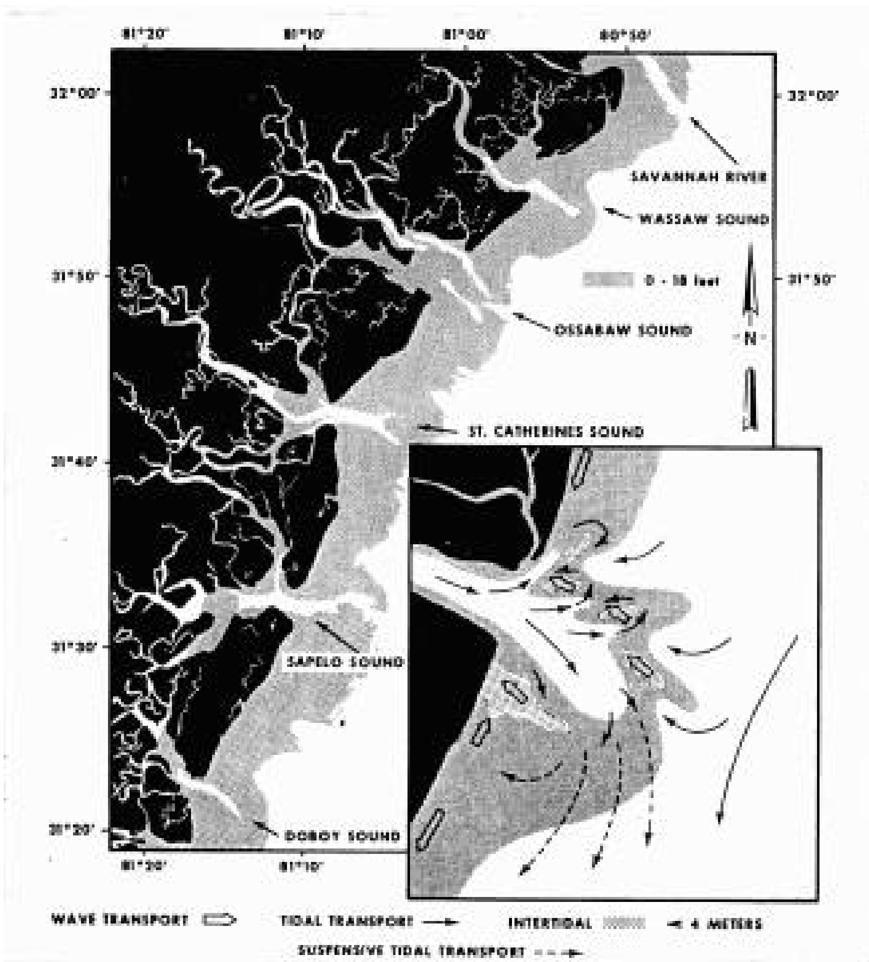

Figure 1-21. Water circulation and sedimentation patterns at the mouths of Georgia estuaries. (From Stanley and Swift, 1976; after Oertel, 1972.)

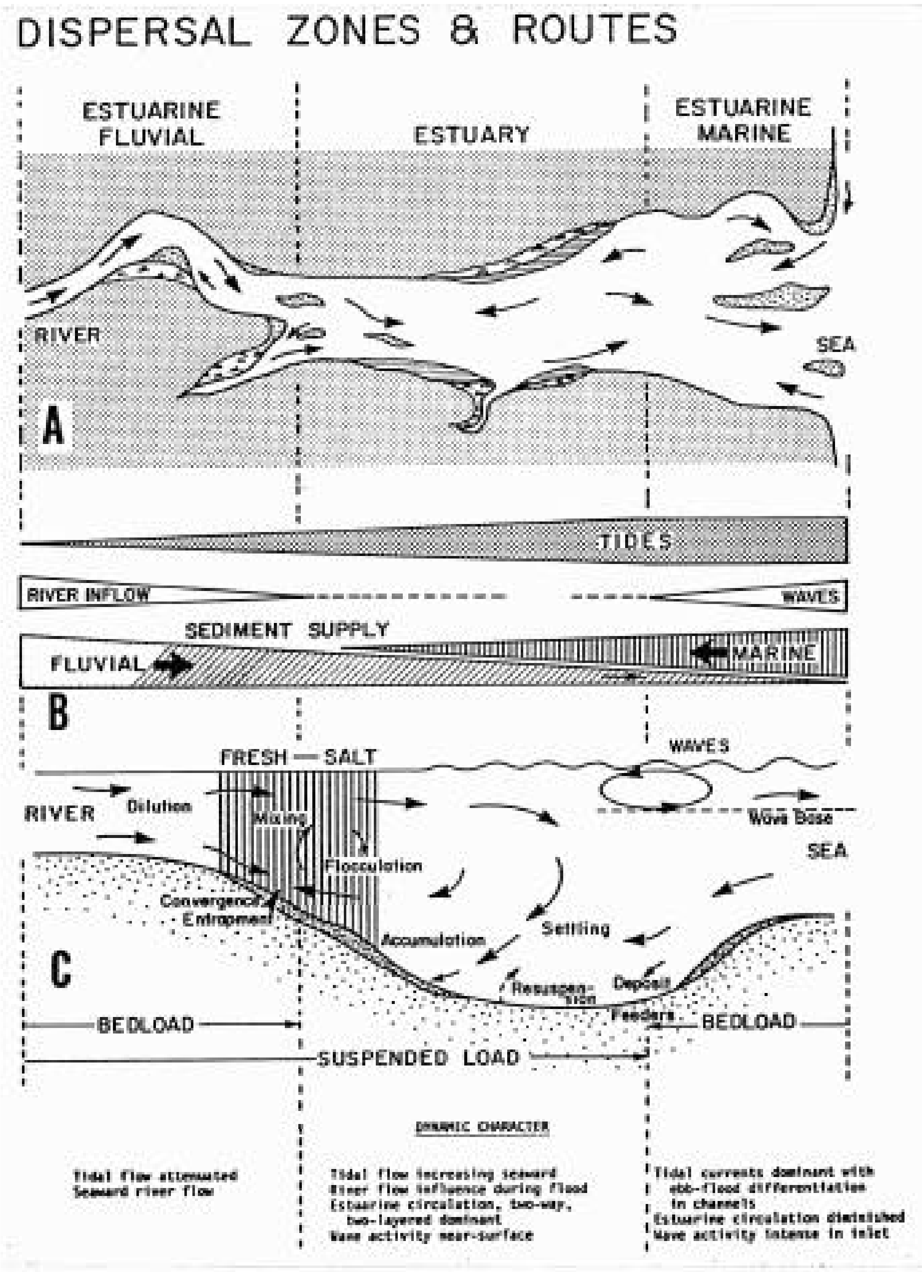

Figure 1-22. Conceptual model of sediment dispersal zones and circulation patterns in a hypothetical, Chesapeake Bay-type estuary. Note presence of zone of turbidity maximum and zone of suspended sediment entrapment in the area where salt and fresh waters mix (cross-section C). (From Nichols and Biggs, 1985; Fig. 2-48.)

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2 Oil Behavior and Toxicity

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Chapter 2.
Oil Behavior and Toxicity

Composition of Crude Oils

Crude oils are complex mixtures which vary widely in composition. However, they can be divided into three broad groups of compounds which help the responder assess the initial impacts and fate of the oil. These groups are very simple:

1) Light-weight components
2) Medium-weight components
3) Heavy-weight components

We use compositional data on crude oils to characterize them as to the amounts of each group present in the oil, and thus predict the behavior of the oil and the risk the oil poses to natural resources of concern.

Light-weight components are characterized by:

- Hydrocarbon compounds containing up to ten carbon atoms
- A boiling range up to 150 degrees C
- Rapid and complete evaporation, usually within a day
- High water solubility; usually contributes >95% of water-soluble fraction
- High acute toxicity because they contain the monoaromatic hydrocarbons (benzene, toluene, xylene) which are soluble and toxic
- No potential for bioaccumulation (they evaporate instead)
- Mostly composed of alkanes and cycloalkanes which have relatively low solubility (and thus low acute toxicity potential)

These light ends evaporate so quickly that they do not persist in the environment. Even though individual aromatic compounds have solubilities of over 1,000 mg/L, they are rapidly removed from solution by evaporation. One important exception to this general rule is when the dissolved fraction is rapidly mixed into the water column under cold conditions, as occurred during the Ashland spill of over 1 million gallons of No. 2 fuel oil into the Monongahela River on 2 January 1988. To make conditions even worse, the spill flowed over numerous locks and dams, which caused the oil to mix throughout the water column as it plunged over the dams. Dissolved and dispersed oil was detected in the river for hundreds of miles downstream.

Medium-weight components are characterized by:

- Hydrocarbon compounds containing between 10 and 22 carbon atoms
- A boiling range from about 150 to 400 degrees C
- Evaporation rates of up to several days, although there will be some residue which does not evaporate at ambient temperatures
- Low water-soluble fraction (at most a few mg/L)
- Moderate acute toxicity because they contain diaromatic hydrocarbons (naphthalenes) which are toxic in spite of their low solubilities
- Moderate potential for bioaccumulation and chronic toxicities associated with the diaromatic hydrocarbons
- Alkanes which are readily degraded

These medium-weight components pose the greatest environmental risks to organisms because the compounds are more persistent, they are biologically available, and the PAHs have high toxicities. The alkanes (aliphatic hydrocarbons) are readily biodegraded under the right conditions. In fact, chemists monitor the distribution of these compounds over time to show the process of degradation of a spill.

The heavy-weight components are characterized by:

- Hydrocarbon compounds containing more than 20 carbon atoms
- Almost no loss by evaporation
- Almost no water-soluble fraction

- Potential for bioaccumulation, via sorption onto sediments, otherwise not highly bioavailable

- Potential for chronic toxicity, because they contain polynuclear aromatic hydrocarbons (phenanthrene, anthracene, etc.)

- Most of the components are waxes, asphaltenes, and polar compounds which do not have any significant bioavailabilites or toxicities

- Long-term persistence in sediments, as tar balls, or asphalt pavements

These heavier components pose little acute toxicity risks, except that due to smothering, because of the very low solubilities of the individual compounds. Animals have to be exposed via a sediment pathway or through the food chain. However, these are the most persistent components of an oil, and degradation rates will be very slow.

Refined petroleum products, in contrast to crude oil, have only a very narrow range of components, and they are characterized according to boiling range fractions.

Weathering Processes at Oil Spills as Applied to Resources at Risk, Oil Persistence, and Cleanup

Evaporation

Evaporation is the single most important weathering process in the first several days of an oil spill (Fig. 2-1). For light, refined products such as gasoline, evaporation will remove 100 percent of the spill within a very short time. For heavy refined products such as No. 6 fuel oil or Bunker C, evaporation will only remove 5-10 percent of the spill. For crude oils, the amount of the spill lost to evaporation can range from 20 to 60 percent. For spills of medium crude oils, a rule of thumb is that 20-30 percent of the oil is lost to evaporation within the first 24 hours!

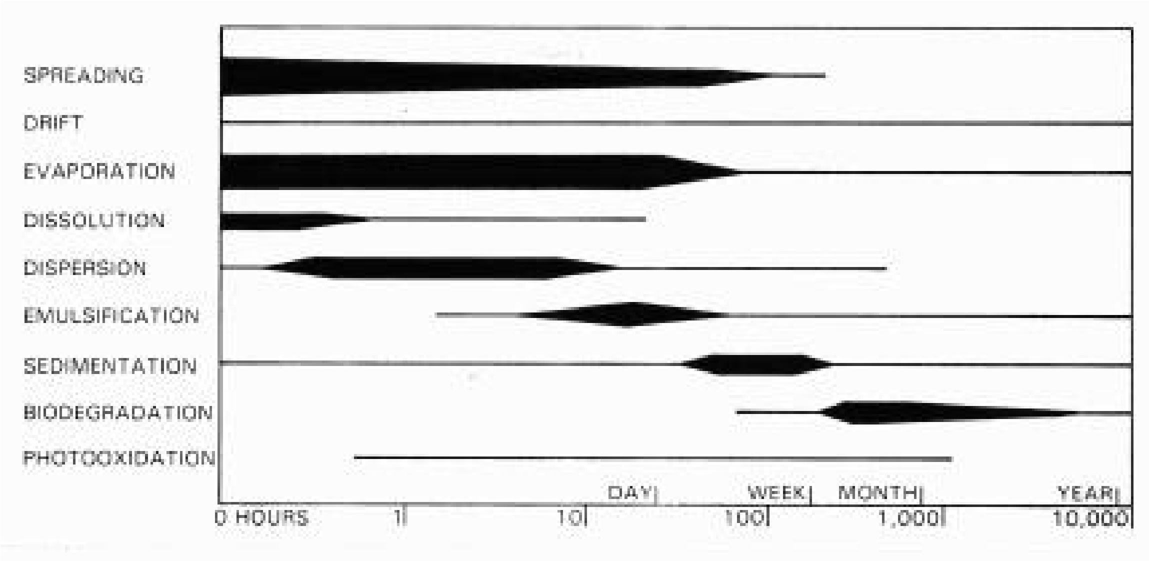

Figure 2-1. Schematic showing the relative importance of weathering processes of an oil slick over time. The width of the line shows the relative magnitude of the process in relation to other contemporary processes.

Payne et al. (1983) have developed an oil-weathering model which has a good evaporation sub-model in it. It uses the true boiling point distillation temperatures and the volume percent of the oil for each of these boiling point ranges, information which is usually available from the owner or shipper. This model is available for use on microcomputers, and it is relatively easy to use. The differences in the rate of evaporation for various oils can be shown by running the model for two different spills: the *Exxon Valdez* spill of Prudhoe Bay crude, a medium-heavy oil, spilled under cold conditions (March 1989), where 10 percent was calculated to have evaporated within the first 24 hours; and the *Mega Borg* spill of Angola crude, a light oil, spilled in June 1990, where 45 percent was calculated to have evaporated within the first 24 hours.

Environmental factors which affect the rate of evaporation are:

- Area of slick exposed, which changes rapidly
- Wind speed and water surface roughness
- Air temperature and solar radiation
- Formation of emulsions, which dramatically slows evaporation

Windy, sunny days and currents which rapidly spread the slicks speed evaporation. Evaporation even removes dissolved hydrocarbons from the water column. Figure 2-2 shows the concentration of the volatile aromatic hydrocarbons in the water-soluble fraction of Prudhoe Bay crude over time as measured in laboratory tests. These compounds are lost via evaporation from the water.

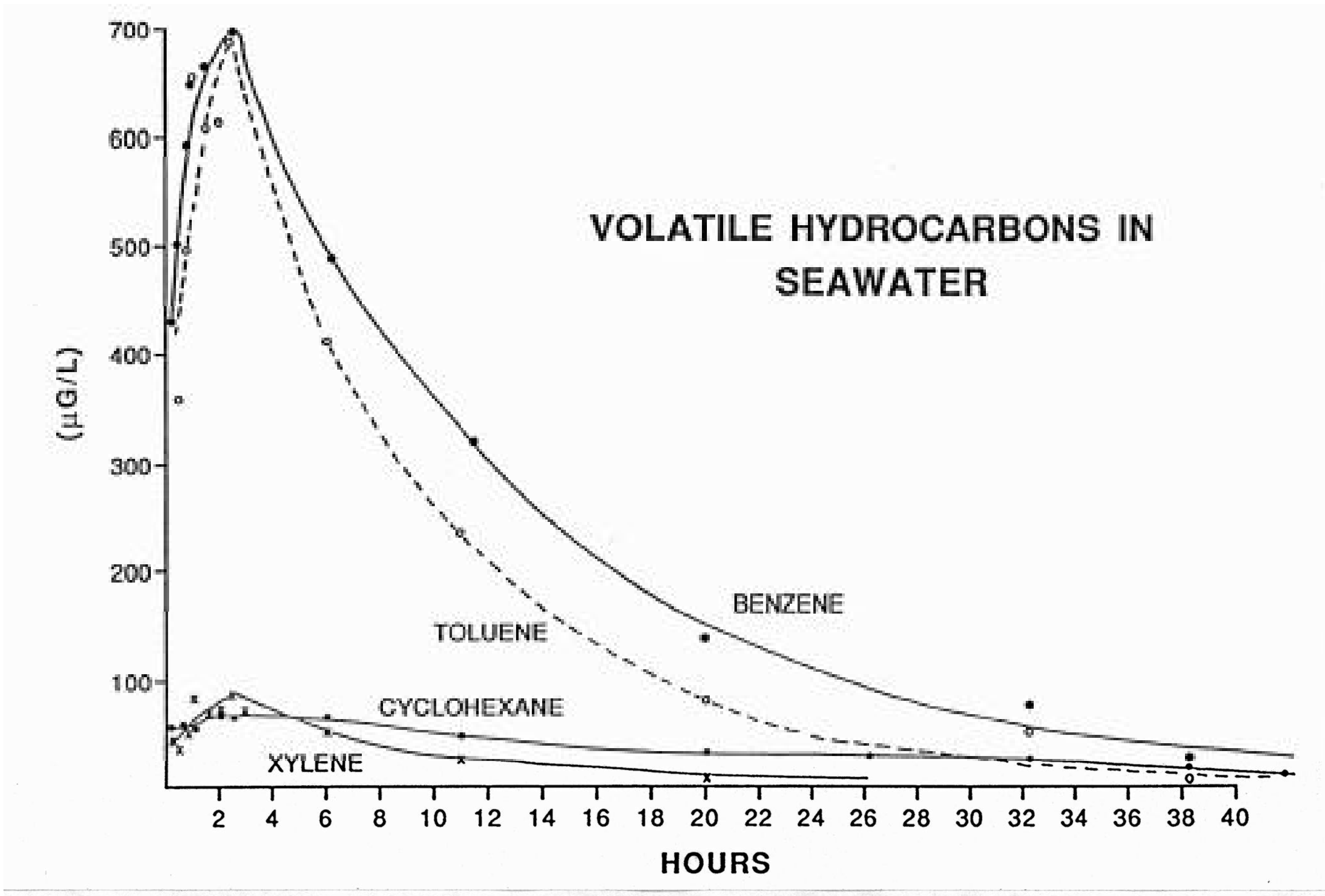

Figure 2-2. Plot of the concentrations of volatile aromatic hydrocarbons in the water-soluble fraction of Prudhoe Bay crude oil over time. Note the rapid loss of these compounds by evaporation (Payne et al., 1983).

Dissolution

Dissolution of petroleum hydrocarbons into the water column poses risks to aquatic organisms because of the acute toxicity of the compounds that have significant water solubility. Figure 2-3 shows the solubility of normal alkanes, cycloalkanes, and aromatic hydrocarbons in fresh water. It should be noted that solubilities in sea water are lower, by about 70 percent (Sutton and Calder, 1974). Compounds with

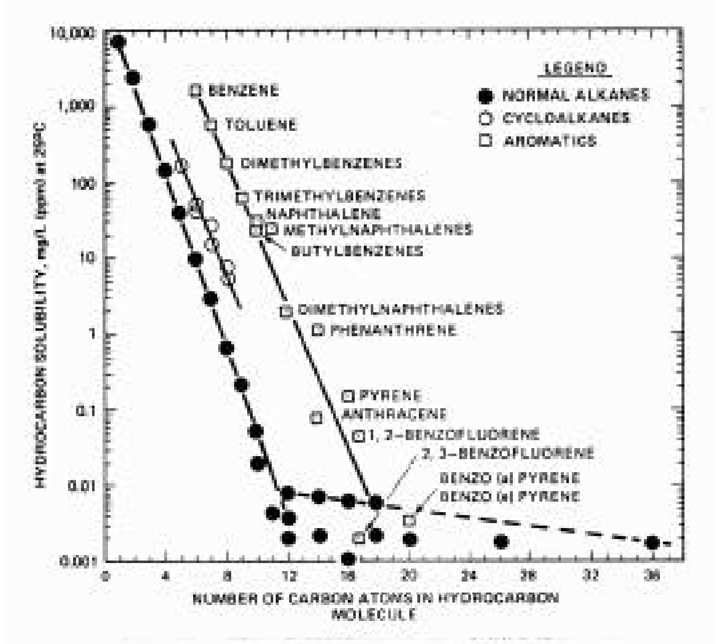

Figure 2-3. Water solubility of the major components of crude oil, for three groups of compounds, plotted by carbon number. (McAuliffe, 1983)

carbon numbers less than four are gases at ambient temperatures, so they are not of concern. The monoaromatics have the highest solubilities, by a factor of 50, than similar weight alkanes. Benzene has the highest solubility, at 1,750 mg/L, with toluene at 515 mg/L, and xylene less than 100 mg/L. McAuliffe (1987) reported the water-soluble fraction of six oils equilibrated with saline water, ranging from 20 to 40 ppm total dissolved hydrocarbons. Benzene plus toluene constituted from 70-85 percent of the aromatic fraction, and total aromatics constituted 35-80 percent of the total dissolved hydrocarbons. Of the higher PAHs, naphthalene is the most water-soluble, contributing 0.12 ppm to the water-soluble fraction of south Louisiana crude and 0.02 ppm for Kuwait crude (McAuliffe, 1987). The amount of the next heavier PAHs in the water-soluble fraction is 100 times lower than the naphthalenes.

Emulsification

Formation of emulsions affects the behavior of an oil spill in many ways. First, weathering rates are much slower. The oil is more viscous and sticky. The volume of "oil" is increased by a factor of 2-3, because the emulsion is up to 70 percent water. Most recovery equipment works very poorly on mousse. Tendency to emulsify and emulsion stability is very closely related to the asphaltene content. Predicting the formation and stability of emulsion is important. Based on laboratory and field experience, stable emulsions are likely to form for:

- Heavy crudes with high viscosities
- Crudes and refined products with high asphaltene content
- Crudes with high NSO compound content

Emulsification almost never occurs during spills of:

- Gasoline
- Kerosene
- Diesel fuels (except under VERY cold conditions)

General Spill Types and Behaviors

Based on all the properties of spilled oil, there are four types of oil for which a general assessment of the behavior and fate can be made:

Type 1—Very Light Oils (Jet Fuels, Gasoline)

- Highly volatile (should all evaporate within 1-2 days).
- High concentrations of toxic (soluble) compounds.
- Result: Localized, severe impacts to water column and intertidal resources.
- Duration of impact is a function of the resource recovery rate.
- No dispersion necessary.
- No cleanup necessary.

Type 2—Light Oils (Diesel, No. 2 Fuel Oil, Light Crudes)

- Moderately volatile; will leave residue (up to one-third of spill amount) after a few days.
- Moderate concentrations of toxic (soluble) compounds, especially distilled products.
- Will "oil" intertidal resources with long-term contamination potential.

- Has potential for subtidal impacts (dissolution, mixing, sorption onto suspended sediments).
- No dispersion necessary.
- Cleanup can be very effective.

Type 3—Medium Oils (Most Crude Oils)

- About one-third will evaporate within 24 hours.
- Maximum water-soluble fraction 10-100 ppm.
- Oil contamination of intertidal areas can be severe and long-term.
- Oil impacts to waterfowl and fur-bearing mammals can be severe.
- Chemical dispersion is an option within 1-2 days.
- Cleanup most effective if conducted quickly.

Type 4—Heavy Oils (Heavy Crude Oils, No. 6 Fuel Oil, Bunker C)

- Heavy oils with little or no evaporation or dissolution.
- Water-soluble fraction is less than 10 ppm.
- Heavy contamination of intertidal areas likely.
- Severe impacts to waterfowl and fur-bearing mammals (coating and ingestion).
- Long-term contamination of sediments possible.
- Weathers very slowly.
- Chemical dispersion seldom effective.
- Shoreline cleanup difficult under all conditions.

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3 Sensitivity of Coastal Environments to Oil

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Chapter 3.
Sensitivity of Coastal Environments to Oil

Introduction

Intertidal habitats are at risk during spills because of the high likelihood of being directly oiled when floating slicks impact the shoreline. Oil fate and effects vary significantly by shoreline type, and many cleanup methods are shoreline-specific. The concept of mapping coastal environments and ranking them on a scale of relative sensitivity was originally developed in 1976 for lower Cook Inlet (Michel et al., 1978). Since that time, the ranking system has been refined and expanded to cover shoreline types for all of North America, including the Great Lakes and riverine environments.

Prediction of the behavior of oil on intertidal habitats is based on an understanding of the coastal environment, not just the substrate type and grain size. The sensitivity of a particular intertidal habitat is an integration of the:

1) Shoreline type (substrate, grain size, tidal elevation, origin),
2) Exposure to wave and tidal energy,
3) Analysis of the natural persistence of the oil on the shoreline,
4) Biological productivity and sensitivity, and
5) Ease of cleanup without causing more harm.

All of these factors are used to determine the relative sensitivity of shorelines. Key to the sensitivity ranking is an understanding of the relationships between physical processes and substrate which produce specific geomorphic shoreline types and predictable patterns in oil behavior and sediment transport patterns. In the following sections, the definition, morphology and processes, and oil behavior for six general coastal environments are summarized.

Exposed Rocky Coasts

Although exposed rocky coasts can be highly variable in elevation, slope, exposure, crenulation, and biological utilization, they can be divided into two broad types, based on the behavior and persistence of oil: wave-cut cliffs and wave-cut rock platforms. Both types are characterized by strong waves which wash across the intertidal zone and, except where very large waves occur, a rich biological community. In general, oil persistence is low because the oil does not penetrate the substrate and so it is available for rapid removal by wave action. But, both types can have complex micro-environments in the form of sheltered crevices and wave-shadow pockets behind large boulders or offshore rocks. They differ in the slope and width of the intertidal zone, the presence of sediments, and wave reflection patterns. Each type is discussed below.

Wave-cut Cliffs

This shoreline type has a steep intertidal zone with very little width. The rock surface can be highly irregular, with numerous cracks and crevices. Sediment accumulations (gravel- to boulder-sized material) are uncommon and usually ephemeral, since waves remove the debris of mass wasting as the sea cliffs retreat. Wave-cut cliffs are found interspersed with other shoreline types, particularly wave-cut platforms.

The narrowness of the intertidal zone limits to some degree the extent of biological colonization, which must also be able to survive the intense wave action. There is strong vertical zonation of biological communities, with animals dominating the mid- to upper intertidal zone, and algae dominating the lower intertidal zone. Offshore, large kelp beds can occur, providing habitat for a wide range of organisms. The ruggedness and isolation of rocky headlands make them important as nesting sites for seabirds.

Observations at many oil spills have shown that:

- Oil is held offshore by waves reflecting off the steep cliffs
- Any oil that is deposited is rapidly removed from exposed faces
- The most resistant oil would remain as a patchy band at or above the high-tide line
- Impacts to intertidal communities are expected to be of short duration

- An exception would be where heavy concentrations of a light refined product (e.g., No.2 fuel oil) came ashore very quickly
- Greatest impacts are likely to be to birds when present at nesting colonies or feeding in nearshore waters

Because of the low potential for oil accumulation and high degree of natural cleansing, wave-cut cliffs have been ranked as having the lowest sensitivity of all natural intertidal habitats.

Wave-Cut Platforms

Where erosion has formed a flat rock bench within the intertidal zone, it is referred to as a wave-cut platform (or shore platform). The width of platforms can range from a few meters to nearly a kilometer. Somewhat surprisingly, there is no consensus as to how they are formed; studies have proposed, in addition to wave action, ice scouring during either or both glacial and modern periods, salt weathering, mechanical fracture by freeze and thaw action, and biological weakening of the rock. However, it has been shown that many platforms are very young, maybe taking only up to a thousand or a few thousand years to form. (How else could the present platforms keep up with sea-level rise?)

Wave-cut platforms can be characterized as follows:

- They are composed of a rock bench, of highly variable width
- The shoreline may be backed by a steep scarp or low bluff
- There may be a narrow, perched beach of gravel- to boulder-sized sediments at the base of the scarp
- The platform surface is irregular and tidal pools are common
- Small accumulations of gravel can be found in the tidal pools and crevices
- Pockets of sandy "tidal flats" can occur on the platform in less exposed settings
- These habitats can support large populations of encrusting animals and plants, with rich tidal pool communities
- They can be used as haulouts by marine mammals

Even though they are exposed to high wave energy, there are two factors which make wave-cut platforms more sensitive to oil spill impacts than wave-cut cliffs.

First, oil may penetrate and persist longer in the beach sediments, if present. This oil would be removed only when large waves reworked the sediments. There can be a wide variability in the rate of reworking along a shoreline segment, depending upon the width of the platform, fetch, shoreline orientation, and the presence of offshore rocks which refract waves. The latter condition can result in accumulation and persistence of oil due to what we term the *tombolo effect*, which is illustrated in Figure 3-1. A *tombolo* is a spit-like projection of unconsolidated sediment that forms behind an offshore island or bedrock outcrop. The tombolo is the accumulation of sediment which forms as a result of wave refraction bending around the island or bedrock outcrop, where the refracted waves meet in the lee of the offshore obstruction. The important point is that wave energy is lower in the lee of the tombolo, and any stranded oil tends to persist much longer there. For example, Figure 3-1 shows that oil from the *Exxon Valdez* oil spill in Alaska remained over one year in a very high energy setting as a result of the protection (from wave attack) afforded by the offshore rock outcrops on the wave-cut platform.

The second factor which increases the sensitivity of wave-cut platforms is the potential for greater impacts to intertidal communities. Although oil does not adhere to the wet rock surfaces, heavy accumulations of oil can temporarily cover the intertidal zone during falling tides. Tidal pool organisms can be killed by smothering or exposure to the toxic fractions of fresh oil or refined products. Also, marine mammals using the platforms as haulouts can be directly oiled.

Oil behavior on wave-cut platforms can be summarized as follows:

- Oil will not adhere to the rock platform, but rather be transported across the platform and accumulate along the high-tide line
- Oil can penetrate and persist in the beach sediments, if present
- Persistence of oiled sediments is usually short-term, except in wave shadows or larger sediment accumulations

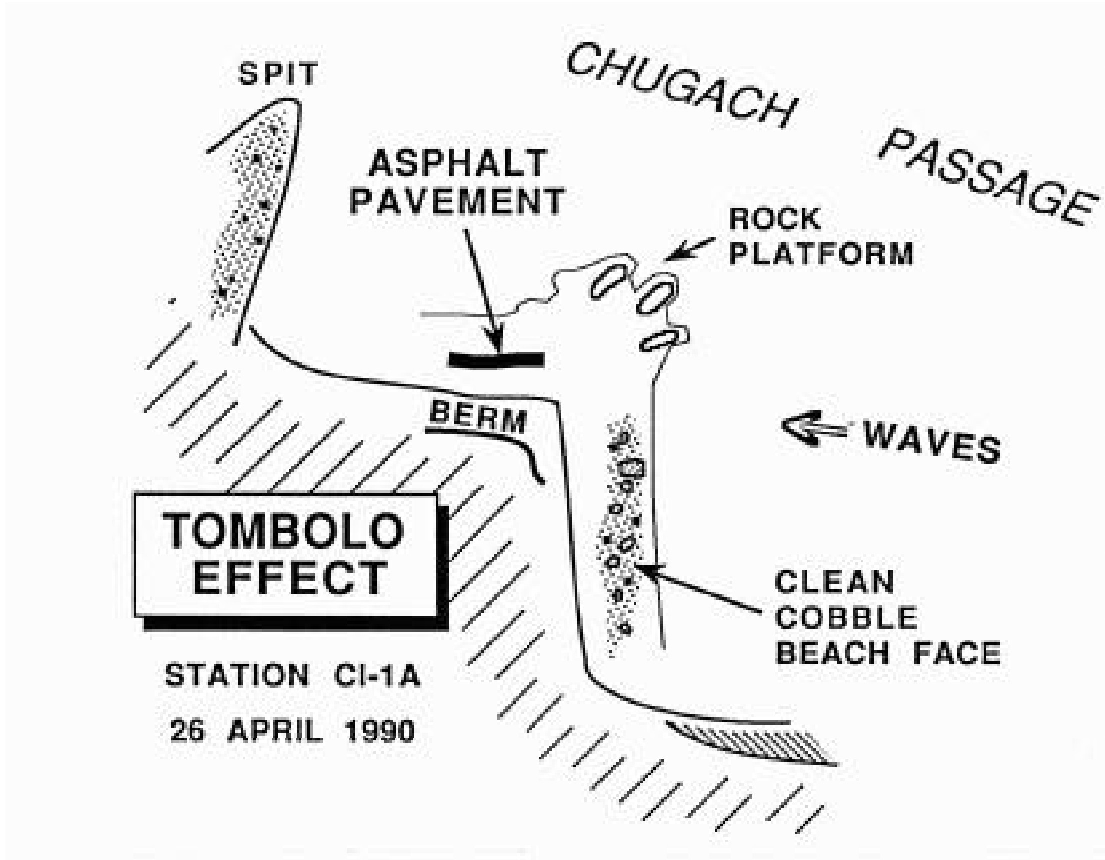


Figure 3-1. Example of the tombolo effect at the *Exxon Valdez* spill site. (From Hayes et al., 1990; Fig. 4.)

Sand Beaches

Introduction

A beach is an accumulation of unconsolidated sediment that is transported and molded into characteristic forms by wave-generated water motion. Beaches will form virtually anywhere sediment is available and there is a site for sediment accumulation. Inherent to sand beaches is change, over timescales ranging from seconds to years. Knowing the patterns of change enables us to better predict the behavior of oil spills and the persistence of oiled sediments. Sand beaches vary widely in their grain size, width, slope, origin, exposure to waves, and sediment transport patterns, and geologists and engineers have devised many types and models to describe them. In contrast, biologists seldom differentiate among sand beaches and consider them to have simple biological communities.

Figure 3-2 shows a typical beach profile and common terminology. Starting at the water level (WL), a low-tide terrace forms a flat, hard-packed, and water-saturated surface. Over this surface, sand which was eroded from the beach by storm waves migrates in the form of intertidal bars (ridges) up to 1 meter in height. The depression in front of the ridge is called a runnel. Eventually, the ridge welds onto the beach, forming a berm at the high-tide line. Note that the berm top slopes gently landward, forming a berm runnel. During the depositional stages on a beach, multiple berms can form. It should also be noted that deposition of the berm can build up to 2 meters of sand over a period of weeks to months. The beachface extends from the berm crest to the low-tide terrace and is steeply inclined toward the sea.

From the perspective of oil behavior on beaches, there are three basic factors:

1) The depth of oil penetration into the sediments

2) The potential for burial of oiled layers by clean sediments

3) The ability of the sediment to support equipment

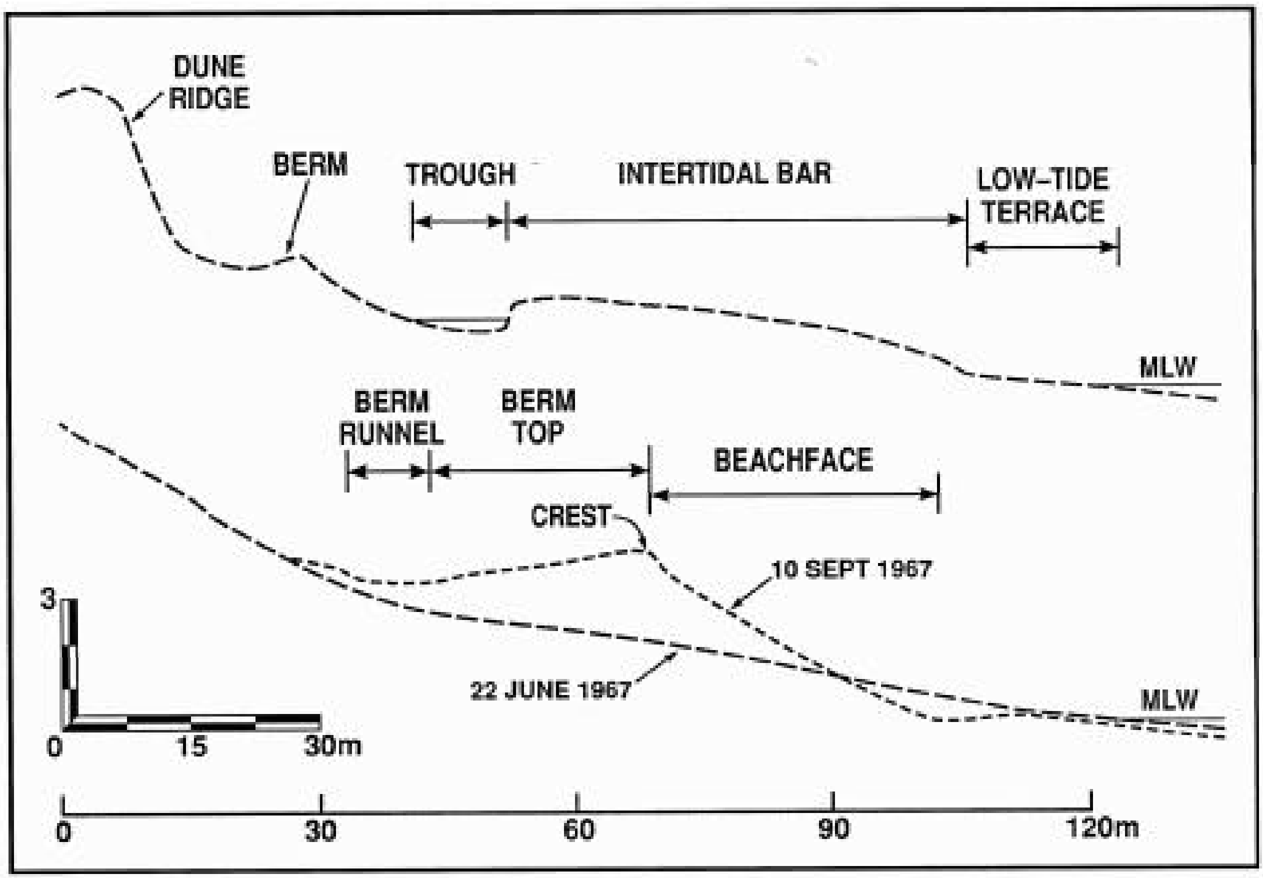


Figure 3-2. Three of the more common types of beach profiles occurring on sand beaches. Examples from Plum Island, Massachusetts. The upper profile, a constructional profile, occurs when beach is recovering from an erosional episode. The intertidal bar migrates landward, accretes to the beach, and a major accretional berm (mature profile; one labeled 10 Sept. 1967) results. The flat, post-storm profile (labeled 22 June 1967) occurred after a brief summer storm. (After Hayes and Boothroyd, 1969; Figs. 4 and 5.)

Morphology and Sediment Transport

The grain size of a beach shows a distinct relationship to the slope of the beachface– the coarser the sand, the steeper the beachface. The beach slope is also controlled by wave activity in that eroding beaches tend to flatten and accreting beach steepen. Figure 3-3 illustrates the relationship of beach slope to grain size and degree of exposure. Knowledge of the sediment transport patterns for sand beaches is important for understanding how oil behaves on them.

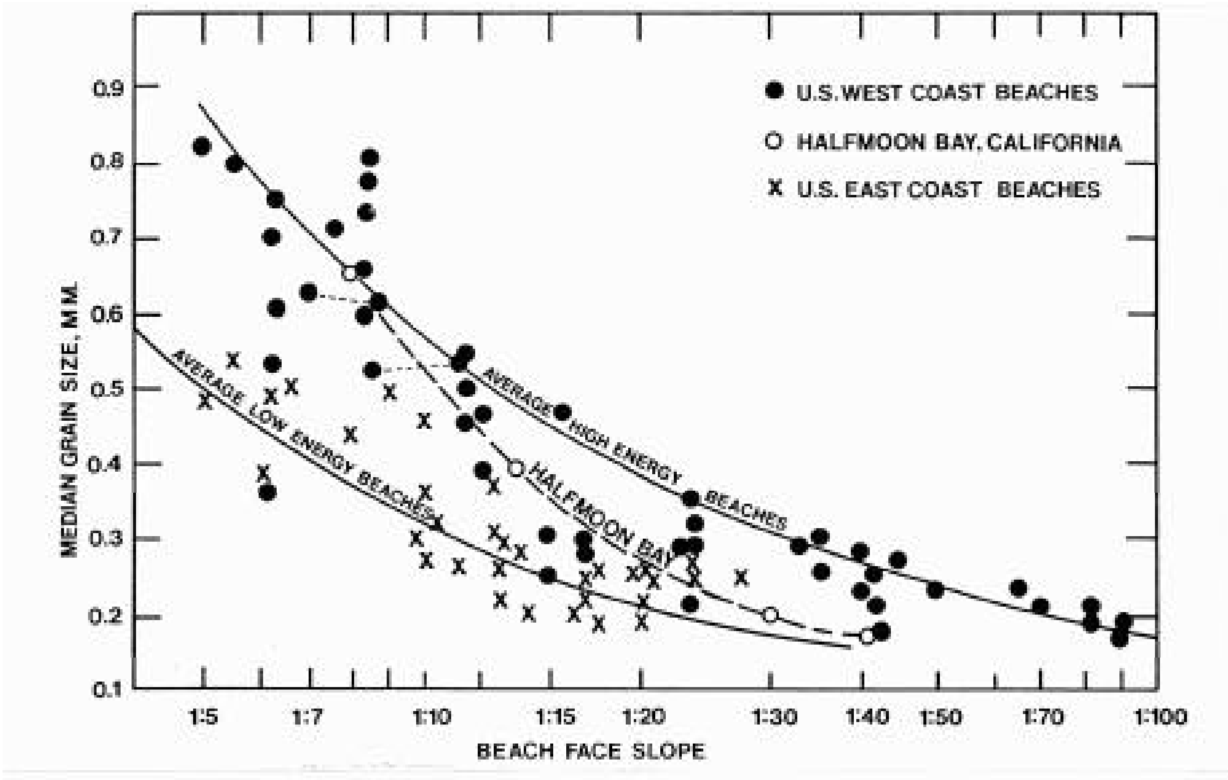


Figure 3-3. Relationship of beach grain size to beachface slope on the east and west coasts of North America. The more exposed beaches of the west coast tend to have flatter slopes because of the large volumes of backwash produced by the larger waves. Halfmoon Bay, California, is partially sheltered by a headland, so its data points fall between the two extremes. (From Komar, 1976, Fig. 11-8; based on data of Bascom, 1951 and Wiegel, 1946.)

Sand is moved alongshore on beaches by two mechanisms. Under oblique wave approach, the paths of moving sand grains on the beachface follow a saw-tooth pattern as the wave uprush pushes the grains obliquely up the beach and they roll straight down the slope as gravity pulls back the backwash. Also, the continuous action of the oblique waves induces a longshore current which carries sediment parallel to shore. Both processes are simply illustrated in Figure 3-4, although complex sediment circulation patterns can form complicated bar and rip systems.

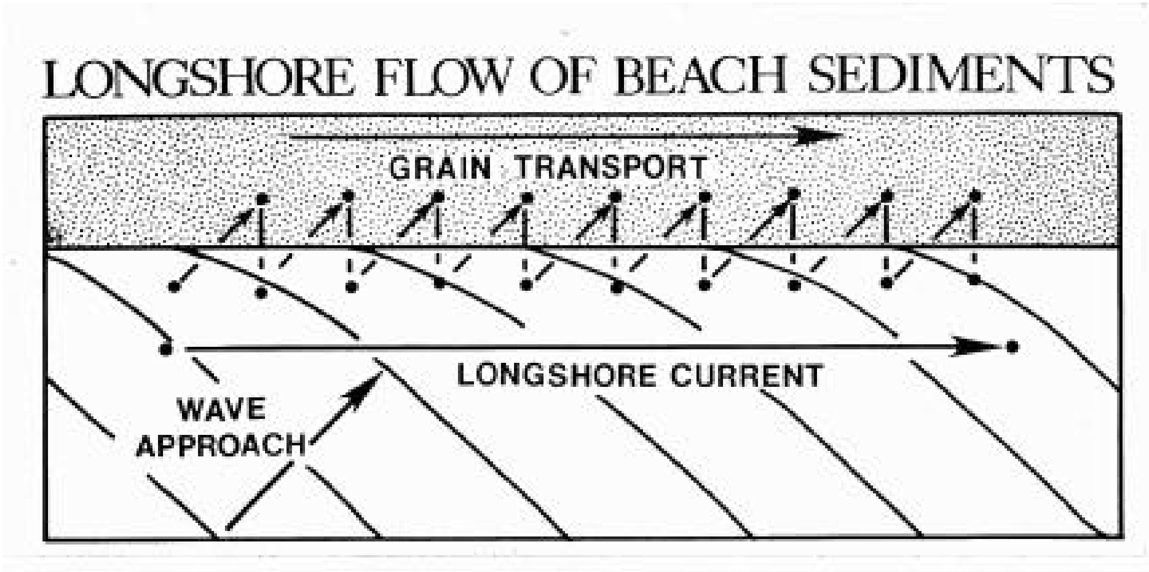


Figure 3-4. Longshore motion of beach sediment produced by wave swash and wave-generated current action when waves approach the shoreline at an angle. (From Bird, 1968.)

The erosion and deposition of sand on beaches is known as the ***beach cycle***. The concept of the cyclical change of beaches from a flat, erosional profile in winter to a wide, depositional berm in summer is well ingrained in both the popular and scientific literature. The concept originated from detailed studies on the west coast of the United States (Shepard, 1950; Bascom, 1954). Generally speaking, storm waves which erode sand from the beach are more common in the winter, whereas flatter, depositional swell waves are more common in the summer on the California coast– hence the terms *summer* and *winter* profiles. Figure 3-5 shows the deposition at Carmel, California during the summer and the subsequent erosion triggered by big winter storms. However, this strong seasonal storm pattern is not present along other coasts, and the more appropriate terminology is to refer to the beach profile as the post-storm, constructional, or mature (fully accretional) profile.

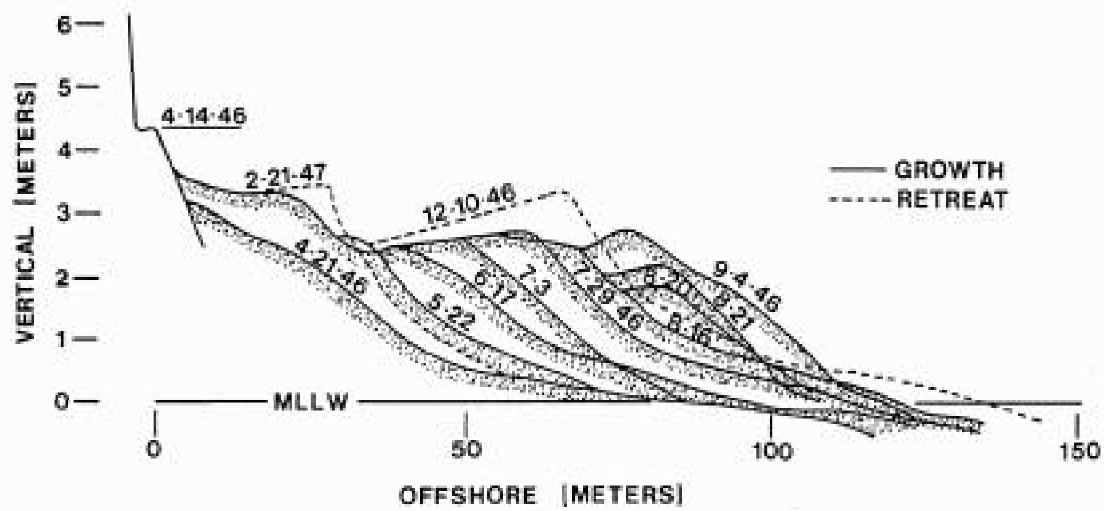


Figure 3-5. Growth and retreat of beach berm at Carmel, California between 14 April 1946 and 21 February 1947 (after Bascom, 1954). These and other observations on the California coast gave birth to the concept of <u>winter</u> and <u>summer</u> beach profiles.

The stage of the beach cycle determines the rate and amount of sediment accumulation on beaches, and hence the potential for burial of oiled layers by clean sand or removal of oiled sediment by erosion. For oil spill analysis, sand beaches can be divided into two basic types, fine-grained and coarse-grained, which are compared and contrasted in the following sections.

Fine-grained Sand Beaches

The grain size of sediment on fine-grained sand beaches ranges between 0.0625 and 0.25 millimeters (mm). The compact sediments prevent deep penetration of oil. On exposed shorelines, the beaches are generally flat, wide, and hard-packed. Along more sheltered bays and lagoons, the beaches are still flat but much narrower and commonly fronted by tidal flats. Because of this flat profile, they change very slowly in response to changing wave and tidal conditions. The importance of this characteristic is best exemplified by observations at the *Urquiola* oil spill in Spain in 1976, shown by sequential beach profiles of a heavily oiled fine-grained sand beach in Figure 3-6 and described by Gundlach et al. (1978).

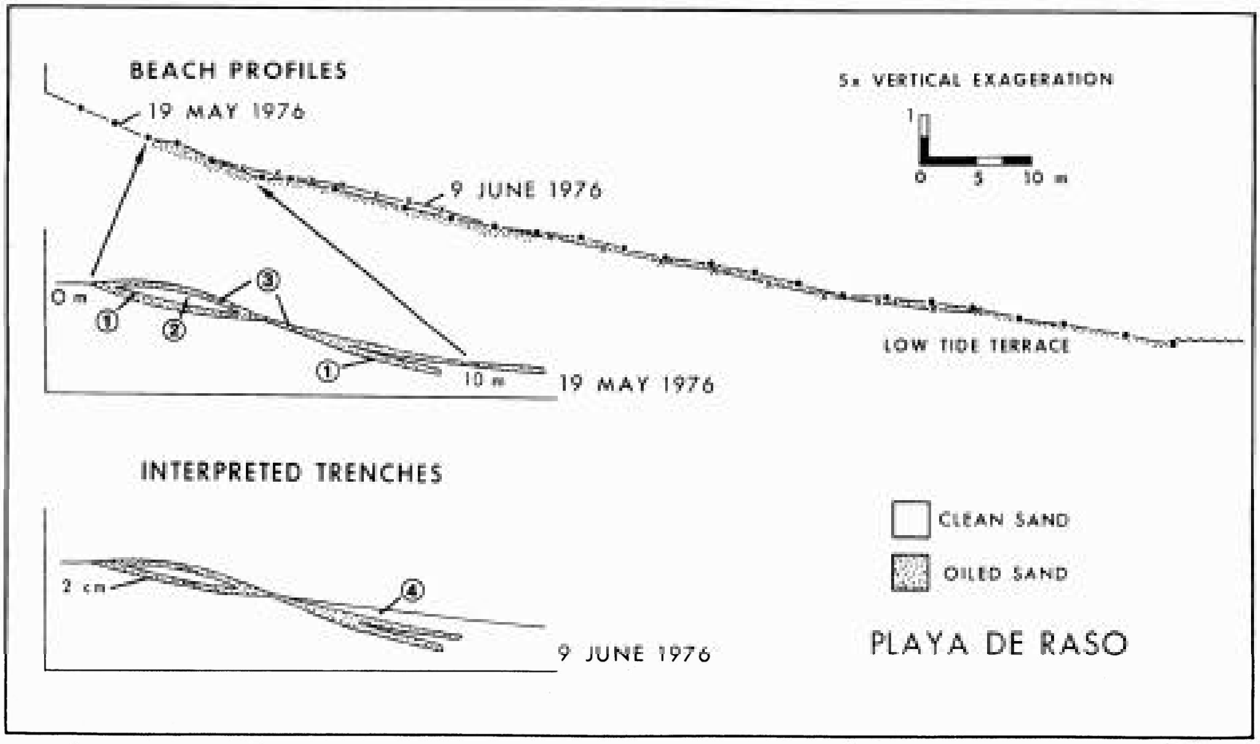


Figure 3-6. Beach profiles at the *Urquiola* oil-spill site, Plaza de Raso, Spain, plotted at 5:1 vertical exaggeration. Note the relatively shallow depths of oil penetration and burial on this fine-grained sand beach. Trenches are not drawn to scale. Circled numbers refer to the chronological sequence of depositional events (see text). (After Gundlach et al., 1978; Fig. 7.)

"Initially, 1-3 cm of oil covered the entire intertidal zone. The oil coating was strictly superficial owing to the close packing of the sediment. Comparison of the profiles taken on May 19 and June 9 (Fig. 3-6) illustrates minor, though important, variations in the morphology of the beach. During this time, the lower beachface lost 2 cm of sediment and oil, while the upper portions gained an equal amount of clean sediment. As a result of these subtle changes, oil was removed from 60 m of shore and buried along 23 m.

"Trenches dug in the oiled zone yield substantial information concerning the depositional history of the beach during and after initial oil impact. Interpreted trenches, illustrated in Figure 3-6, indicate the following depositional sequence: (1) burial of the oil deposited on the beachface before measurement of the first profile on May 19, (2) deposition of 3 cm of clean sand on the berm, (3) deposition of the thin surficial oil layer visible on the May 19 profile, and (4) deposition of clean sand over the oiled layers along the upper portion of the beach. Oil that was placed on the berm during the high spring tides of mid-May remained undisturbed throughout the study period."

The most important of these observations are that oil penetration was limited to a few centimeters and maximum burial of oil anywhere on the beach was about 10 cm. Measurements of oil penetration and burial were made at 19 heavily oiled beaches at the *Urquiola* oil spill, and the results are plotted in Figure 3-7. There is a good correlation between oil penetration and burial with grain size. Maximum penetration in fine-grained sand beaches was less than 10 cm and maximum burial over a three-week period was less than 20 cm.

Similar results have been observed at many other spills. Since most of the oil remains on or near the surface on fine-grained sand beaches, natural removal processes can be very effective, depending upon the frequency of storms. Usually, the first moderate storm will remove a significant amount of the oil. For example, oil from the *Ixtoc 1* well blowout accumulated on Texas beaches for nearly 30 days, until a tropical depression passed through, generating 1-2 m waves. After the storm, surveys showed that over 90 percent of the oil on the shoreline had been removed (Fig. 3-8), with no buried oil found on any of the fine-grained sand beaches. Only the mixed sand and shell beaches retained a significant amount of oil (Gundlach et al., 1981). Figure 3-9 shows the comparison of the changes in beach profile and oil distribution on fine-grained versus coarse-grained sand and shell hash beaches at the *Ixtoc 1* site. The storm completely reworked the fine-grained sand and removed all of the oil except for a light accumulation of tarballs at the landward limit of wave swash. On the coarse-grained beach, the storm eroded the beachface but deposited a 0.5m thick layer of sediments mixed with tarballs high on the backbeach.

At the *Amoco Cadiz* oil spill in France (March, 1978), most of the fine-grained sand beaches went from being heavily oiled to having a light oil coverage, usually with only a minor oiled swash line, within about a month (Gundlach and Hayes, 1978). By mid-summer, four months later, the fine-grained sand beaches were generally free of oil. However, in some localities, some discontinuous, oiled-sediment layers

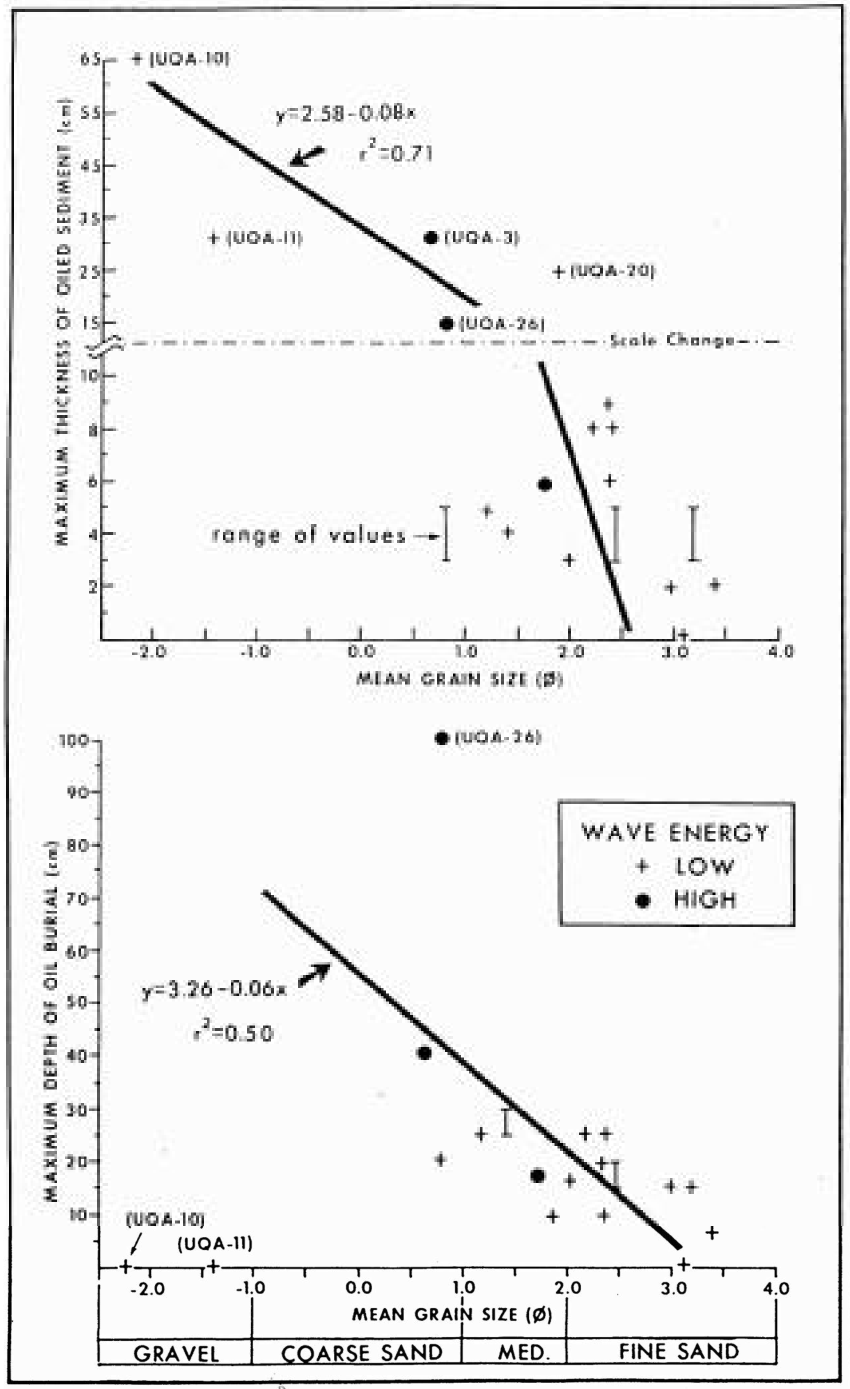


Figure 3-7. Relationship of thickness of oiled sediment layers and oil burial to sediment grain size at 19 oiled beaches at the *Urquiola* oil-spill site. The oil-layer thickness, a function of oil penetration, capillary forces and mixing of sediment and oil by wave action, clearly increases with an increase in grain size (upper curve; correlation coefficient [r^2] = 0.71). Depth of oil burial also increases with increasing grain size (lower curve). (From Gundlach et al., 1978; Fig. 6.)

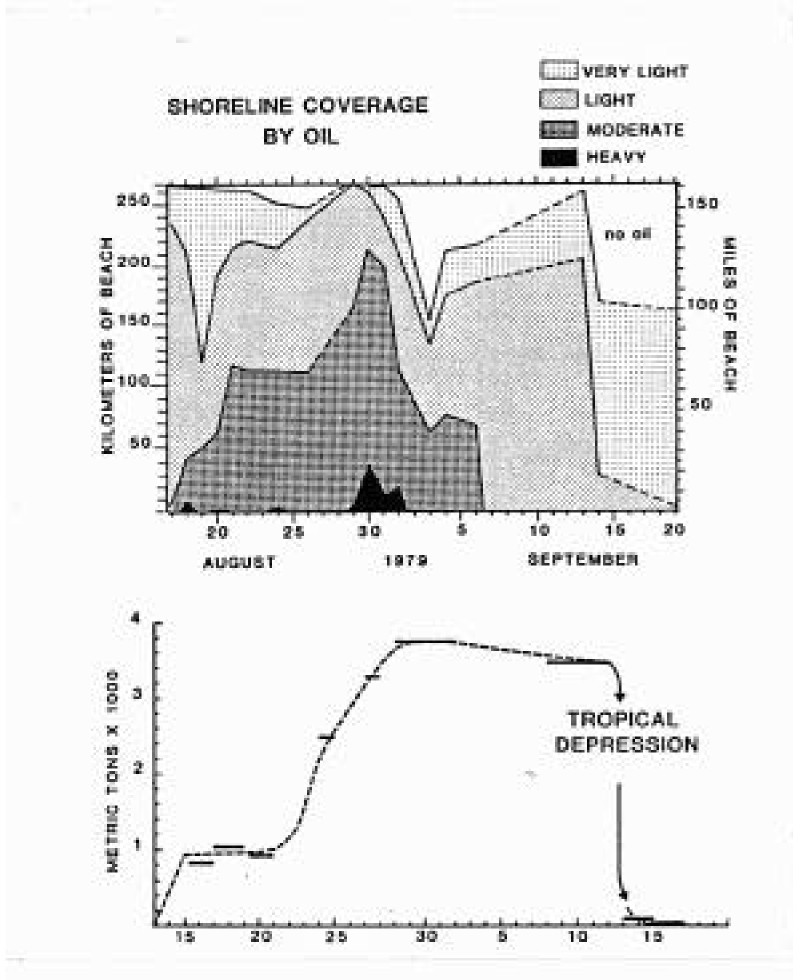


Figure 3-8. Oil coverage along the beach of Padre Island, Texas in August and September 1979 as result of *Ixtoc 1* spill. Note rapid cleaning of the beaches by wave action (1-2 m waves) resulting from passage of a tropical storm on 13 September. (From Gundlach et al., 1981; Fig. 3.)

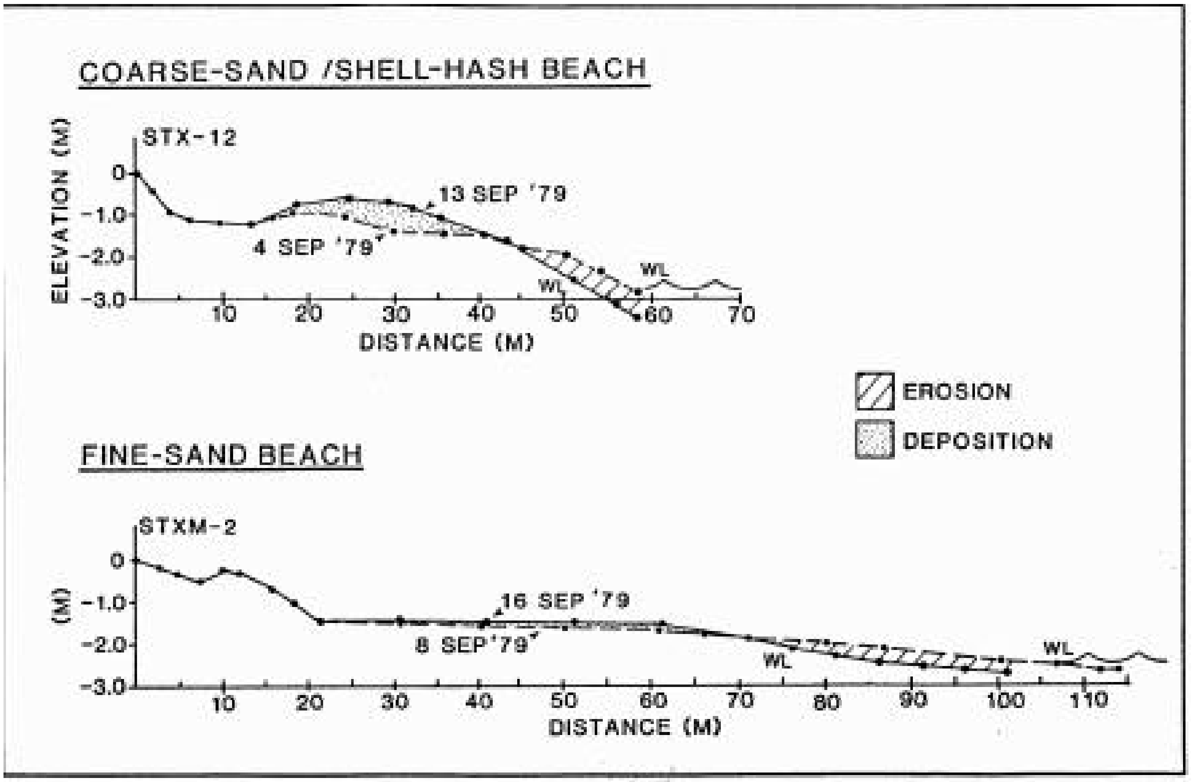


Figure 3-9. Beach profiles of two south Texas beaches that were oiled during the *Ixtoc 1* spill. The changes shown, brought about by the passage of a tropical storm, resulted in oil burial up to 70 cm on the coarse-sand/shell-hash beach and removal of most of the oil from the fine-grained sand beach. (From Gundlach et al., 1981; Fig. 6.)

persisted along the upper beachface until November 1978. All of the fine-grained sand beaches were located along the outer coast, in relatively exposed settings.

In more sheltered settings, oil will persist longer, but burial is less likely because of the low wave energy. Therefore, asphalt pavements may form in such areas if they are heavily oiled. In Saudi Arabia and Bahrain, there are asphalt pavements on sheltered sand beaches from spills up to ten years old. Because these types of beaches are narrow, the pavement can cover nearly the entire beachface. Once a pavement forms, it stabilizes the beach sediments to the degree that only very large, infrequent waves can slowly erode them.

Biological utilization of fine-grained sand beaches is usually low because of the lack of a stable, solid surface and the abrasive action of the moving sand. Epibiota are absent to rare, and infauna are found seasonally in low to moderate densities with a low diversity. Of the small, burrowing species, bivalves, polychaete worms, and crustaceans make up significant portions of the infaunal community on exposed beaches. At certain times of the year, large numbers of shorebirds may be present, feeding on these infauna.

The behavior and short-term impacts of oil on fine-grained sand beaches can be summarized as follows:

On exposed beaches:

- During small spills, oil will concentrate in a band along the high-tide line
- Under heavy accumulations, oil can cover the entire intertidal areas, although the oil will be lifted off the lower part of the beach with the rising tide
- Maximum penetration of oil into fine-grained sand will be less than 10 cm
- Burial of oiled layers by clean sand within the first few weeks after the spill will be limited usually to less than 30 cm along the upper beachface
- Deeper burial is possible if the oil is deposited at the beginning of an accretionary period
- Much of the oil will be removed during the next storm
- Biological impacts include temporary declines in infaunal populations, which can also affect feeding shorebirds
- The usually hard, compact sediments will support pedestrian and vehicular traffic

On sheltered beaches:

- More of the beachface can be covered because it is narrow
- Even less oil penetration occurs because the sediments are finer and can contain small amounts of silt and clay
- There is little to no likelihood of burial, except by wind-blown sand
- Depending on the degree of exposure to any waves, oil persistence can increase to months or years

- A moderately rich biological community can be supported
- Asphalt pavements can form under heavy accumulations; pavements will change nature and stability of the substrate and thus its biological utilization

Coarse-grained Sand Beaches

The grain size of sediment on coarse-grained sand beaches ranges between 0.25 and 2 mm. The more porous sediments allow penetration of oil up to 25 cm (Fig. 3-7). On exposed shorelines, the beaches are steeper and softer than fine-grained sand beaches, and the width is highly variable. Along more sheltered bays and lagoons, the beaches are steep but much narrower and commonly fronted by tidal flats. Coarse-grained sand beaches change rapidly in response to changing tidal and wave conditions, again as observed first at the *Urquiola* oil spill.

The processes are shown in Figure 3-10 and discussed by Gundlach et al. (1978), as follows:

> "As oil first came ashore on May 17 or 18, the runnel behind the spring berm acted as a trap for incoming oil. Pools of oil several centimeters thick remained in the berm runnel for several weeks. As inferred from the trenches illustrated in Figure 3-10, the following sequence of events probably occurred during and after initial oil impact. Alternative clean and oiled layers along the upper portion of the beach indicate that: (1) Oil slicks came ashore and were stranded during an accreting stage of spring berm development. Oil continued to come onshore as the tidal stage regressed toward neap. The neap berm formed as a result of constructional wave activity during this tidal stage. (2) Oil deposited at the time rapidly became incorporated into the accreting neap berm. (3) Oil pools formed in the neap berm runnel as more oil slicks came ashore. As the tidal cycle once again advanced toward spring conditions, after neap tides on May 20-23, the neap berm was partially destroyed and its sand distributed higher on the beach. (4) Oil previously deposited in the runnel of the neap berm was buried during this process. Remnants of this deposit are visible as discontinuous layers intersecting the beachface at high angles. During all stages, oiled sediment

was continuously reworked so the main portions of the beach still appeared heavily oiled on June 9, almost four weeks after the grounding."

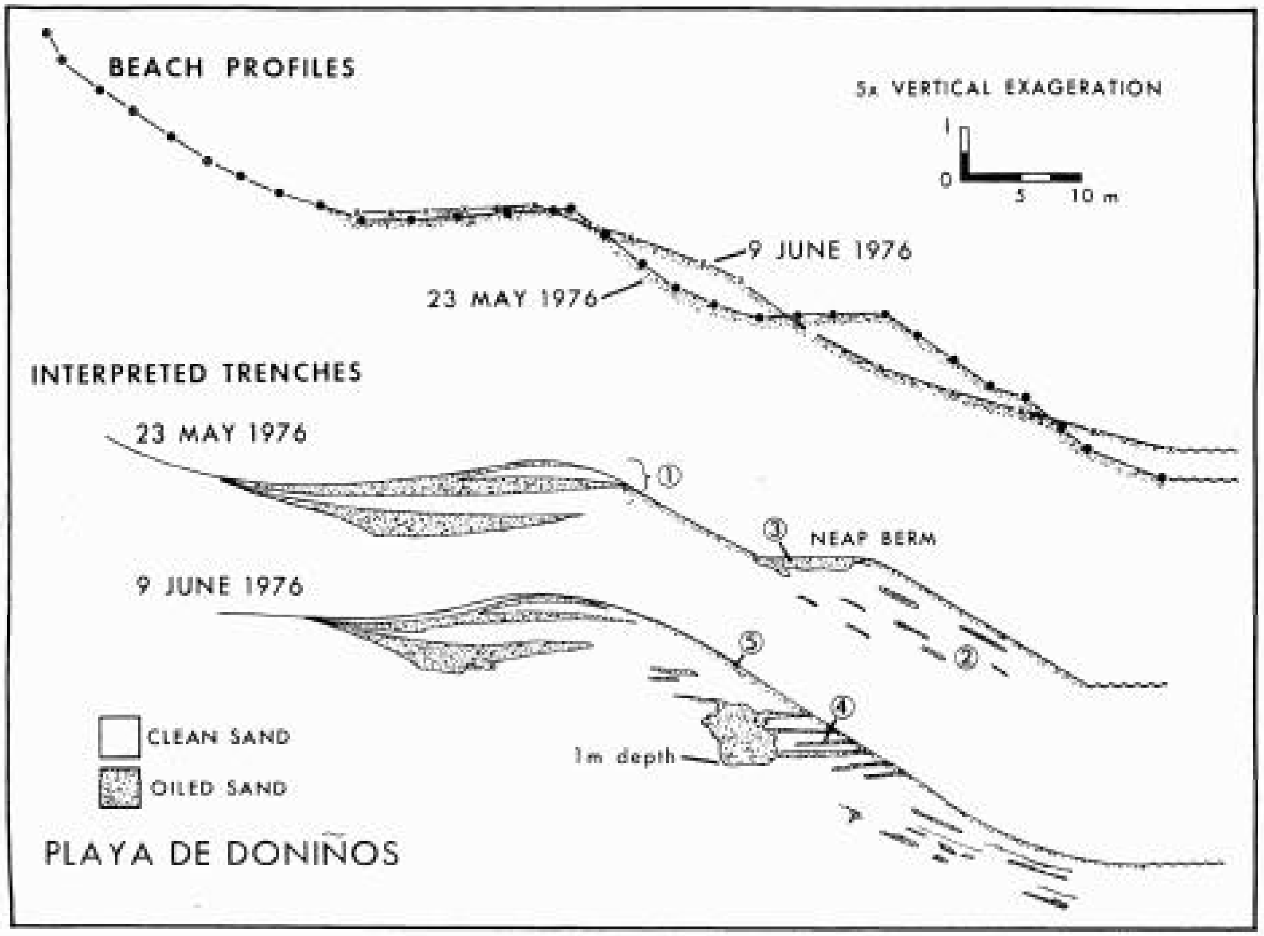


Figure 3-10. Burial of oil as result of beach-profile changes on a moderately oiled medium- to coarse-grained sand beach at the *Urquiola* spill site (Playa de Doñinos, Spain). Numbers refer to chronological sequence of depositional events (discussed in text). Trenches are not drawn to scale. (From Gundlach et al., 1978; Fig. 9.)

Coarse-grained sand beaches pose much greater oil persistence and cleanup problems than fine-grained sand beaches because of the deeper penetration and rapid burial. The stage of the beach cycle at the time of oil deposition will greatly affect the total potential depth of burial. If the oil strands just after a major storm, when the beach is at its erosional maximum, rapid depostion of clean sand can bury the oil until the next storm or perhaps the next storm season (e.g., in California). Figure 3-11 shows sequential profiles from a coarse-grained sand beach at the *Amoco Cadiz* oil spill. Continued deposition of clean sand from March to November resulted in burial up to 82 cm. During the *Ixtoc 1* spill in Texas, coarse-grained sand and shell beaches had a much greater amounts of buried oil than the fine-grained beaches (90 percent versus 37 percent, Fig. 3-12). In California, where there is strong storm seasonality, oil deposited on beaches in March or April could be buried by several meters of clean sediment and re-exposed 6-9 months later, causing re-oiling problems for the shoreline and wildlife.

There is a second mechanism by which oiled layers can be buried by clean sand, namely, migrating rhythmic topography. Figure 3-13 shows the process by which stranded oil could be buried by this alongshore erosional and depositional pattern. This shoreline pattern is most common on beaches with a sustained oblique wave approach.

Because of the mobility of coarse-grained sand beaches, they do not generally support a rich biological community. Some animals may be found in association with beach wrack, mostly amphipods and insects. Burrowing animals can be seasonally low to moderate in densities, but with low diversity and consisting of bivalves, crustaceans, and polychaetes. These beaches can be important resting and feeding habitat for shorebirds and coastal diving birds.

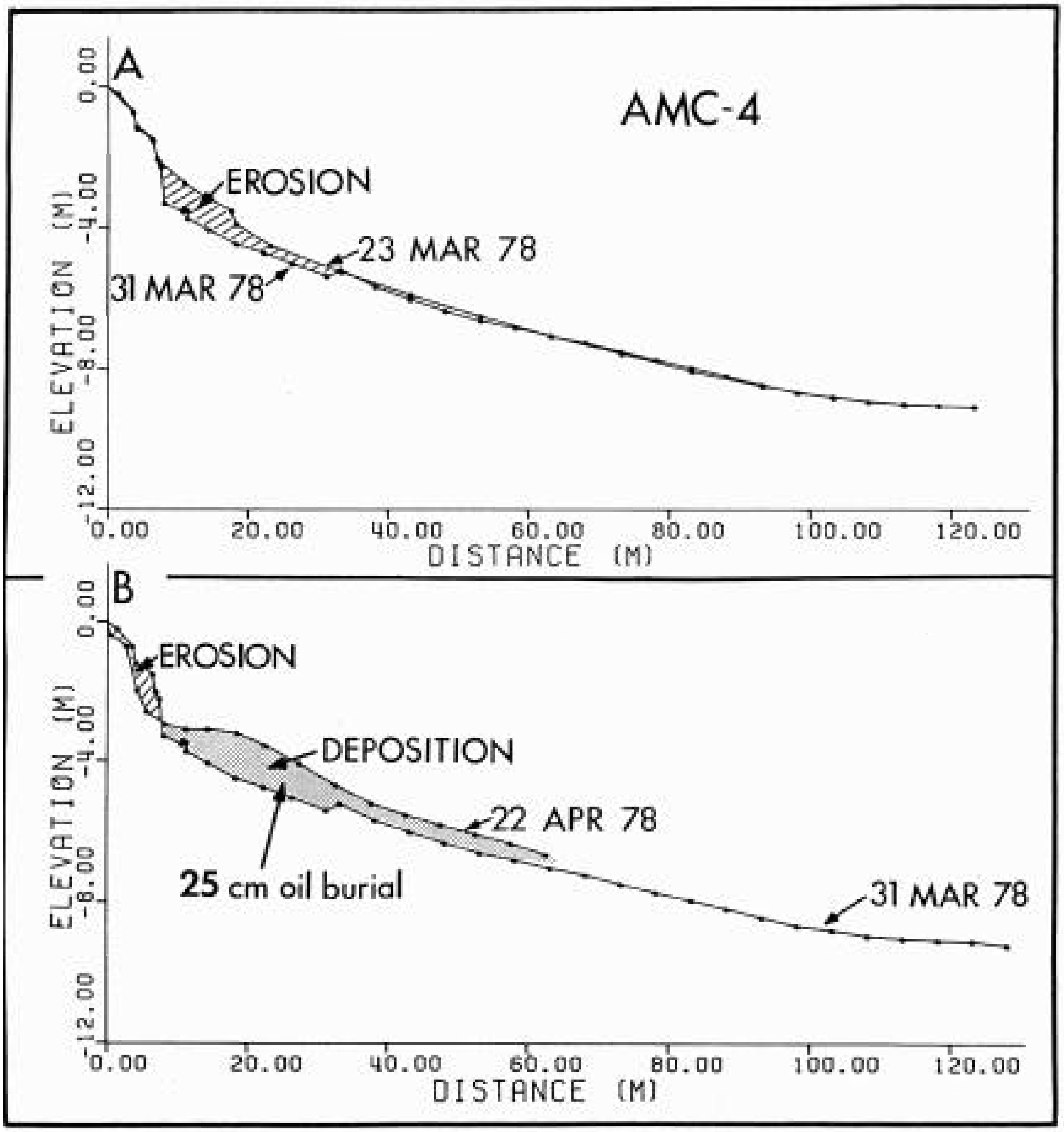


Figure 3-11. Burial of oil as result of beach-profile changes on an oiled sand beach at the *Amoco Cadiz* spill site (Brittany, France). The upper diagram shows loss of sand from the upper part of the profile in late March. Deposition of new sand on the beach between 31 March and 22 April resulted in deep (25 cm) oil burial. The beach continued to accrete, and the oiled zone was buried by 82 cm of sand by November. (After Gundlach and Hayes, 1978.)

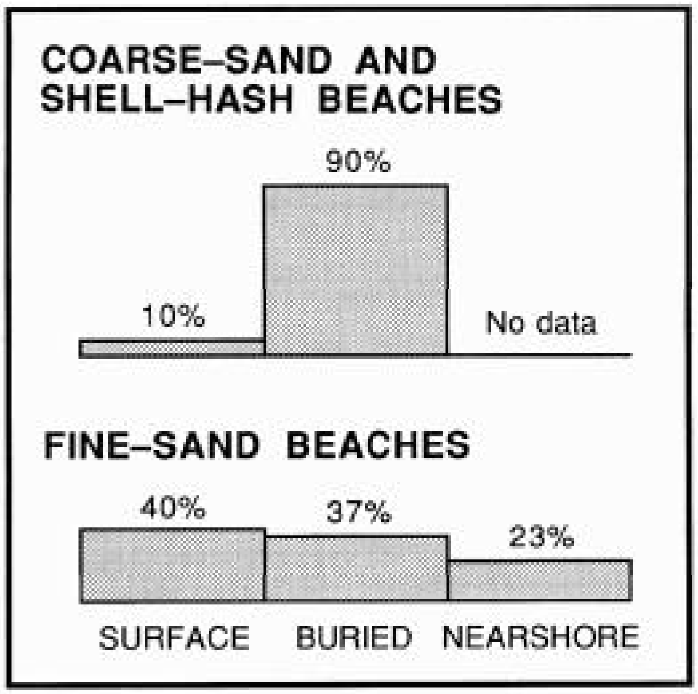


Figure 3-12. Oil occurrence on coarse-sand/shell-hash versus fine-grained sand beaches in South Texas as result of *Ixtoc 1* spill. Note predominance of buried oil in the coarser-grained beaches Based on examination of 16 stations on 3-6 September 1979. (After Gundlach et al., 1981.)

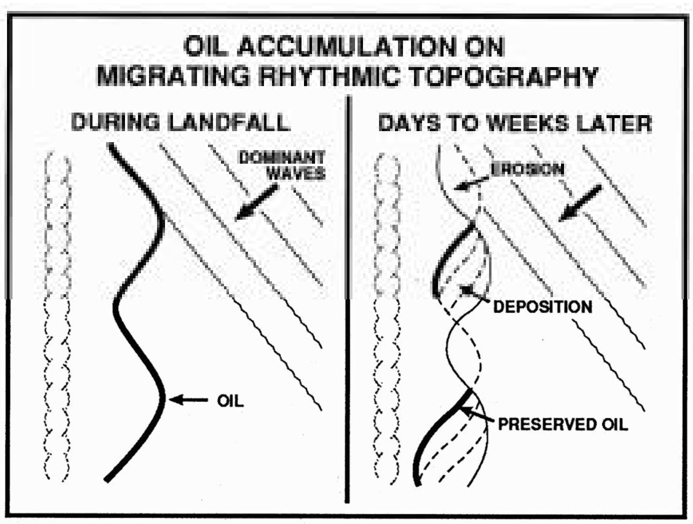


Figure 3-13. Process of oil burial on a beach containing alongshore migrating rhythmic topography. This process was observed at both the *Metula* and *Exxon Valdez* oil-spill sites. (After Hayes and Gundlach, 1975.)

The behavior and short-term impacts of oil on coarse-grained sand beaches can be summarized as follows:

On exposed beaches:

- During small spills, oil will concentrate in a band along the high-tide line
- Under heavy accumulations, oil can cover the entire intertidal zone, although the oil will be lifted off the lower part of the beach with the rising tide
- Large amounts of oil can accumulate in the berm runnel where it is unable to drain off the beach at low tide
- Penetration of oil into coarse-grained sand can reach 25 cm
- Burial of oiled layers by clean sand within the first few weeks after the spill can be rapid, and up to 60 cm or more
- Burial over 1 m is possible if the oil is deposited at the beginning of an accretionary period
- Persistence of deeply buried oil could be long, depending upon the season of year and beach cycle
- Biological impacts include temporary declines in infaunal populations, which can also affect feeding shorebirds
- The sediment can be very soft, making vehicular access difficult

On sheltered beaches:

- More of the beachface can be covered because it is narrow
- Oil penetration will be less where the sediments are finer and more poorly sorted
- Depending on the degree of exposure to any waves, oil persistence can increase to months to years
- Burial by clean sand is still significant but less than exposed beaches
- Asphalt pavements can form under heavy accumulations; pavements will change nature and stability of the substrate and thus its biological utilization

Gravel Beaches

Introduction

Gravel beaches are less well studied than sand beaches and present special problems with regard to the behavior and fate of spilled oil that reaches them. The term gravel refers to a wide range of grain sizes and is further divided into classes as follows:

Class	Size Range
granule	2 - 4 mm
pebble	4 - 64 mm
cobble	64-256 mm
boulder	> 256 mm

Figure 3-14 is a visual estimate chart which shows the gravel classes. The term "rock" is commonly used at spills to refer to gravel, but we recommend that this term be restricted to bedrock or possibly large rubble at the base of cliffs.

Gravel beaches are most common along two types of coastlines–glaciated coasts and rocky, mountainous coasts. Coasts now subject to glaciation, such as the south-central coast of Alaska, typically have gravel beaches along up to 50 percent of their lengths. Areas subject to Pleistocene glaciation, including much of the temperate to subpolar regime of the Northern Hemisphere, also have abundant gravel beaches where the relict glacial deposits are eroding. Erosion of rocky, mountainous coasts, such as those that occur on parts of the outer coasts of Washington, Oregon, and California, also tends to produce gravel beaches.

Gravel beaches are complex features. Research on sediment transport on gravel beaches is quite limited in comparison with work on sand beaches. Sediment transport patterns on gravel beaches are different from those of sand beaches, with gravel being transported landward during storms, forming high berms called *storm berms*, rather than being eroded and deposited offshore. Gravel beaches occur in a very wide range of energy regimes, with complex geologic and topographic settings. Bedrock headlands are usually present, separating isolated gravel beaches. Some gravel beaches are located on straight, open shorelines where they are constantly subjected to large waves. However, many gravel beaches are exposed to significant

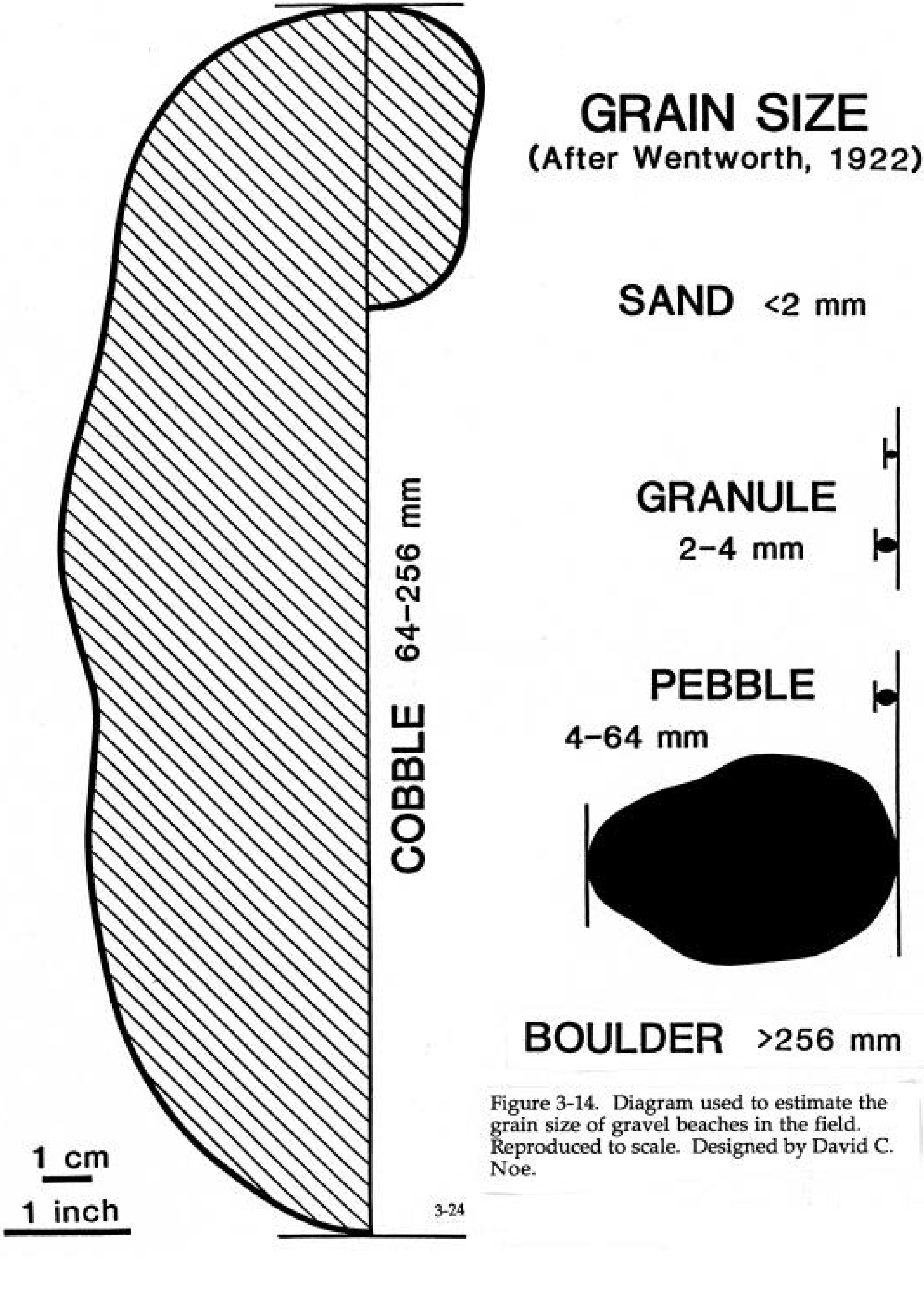


Figure 3-14. Diagram used to estimate the grain size of gravel beaches in the field. Reproduced to scale. Designed by David C. Noe.

wave activity only seasonally, and then only when waves approach from a specific direction. Under these conditions, 1-2 seasons might pass between mobilizing storm events.

Pure Gravel Beaches

Controls of Nature of Gravel Beaches. The internal character of waves is one of the most important determinants of the nature of gravel beaches. Hayes et al. (1991) classified gravel beaches as *reflective* or *dissipative*, according to the types of predominant wave conditions (Fig. 3-15). Reflective waves break close to the beach and are characterized by surging breakers with high run-up and minimum set-up. Reflective gravel beaches show clear evidence of size and shape sorting on steep beachfaces, have multiple cuspate berms, and a narrow directional width of incoming wave angle, which is always shore-normal. Oil deposited on reflective gravel beaches could be buried under the developing berms. In contrast, dissipative waves typically break tens of meters seaward of the beach and dissipate their energy before reaching it. Gravel beaches we classify as dissipate show strong evidence of longshore transport, frequent shifts in wave conditions, and limited swell effects. Where beaches are host to both wave conditions, dissipative waves are more common during storms, with reflective waves more common during calmer periods (Fig. 3-15). During dissipative storm wave conditions, spilled oil may be carried high into the storm berm environment and penetrate into the coarse material above the elevation of normal reworking.

Morphology and Sediments. Figure 3-16 shows a typical profile for a gravel beach exposed to large waves. Note the large, multiple pebble and cobble berms at the upper part of the profile and the eroded, wave-cut platform of the lower part, which is covered with boulders up to a meter in diameter. The grain-size distribution shows the very coarsest material on the outer platform and finer material on the depositional berms, with the storm berm being slightly coarser than the lower-level berms accreted on its seaward face.

On some gravel beaches, a stable armor of coarse material develops over the surface of the middle and lower portions of the beachface (Michel and Hayes, 1991), as illustrated in Figures 3-17 and 18. On a beach which typically has constantly changing current velocities, threshold transport conditions for different particle sizes are frequently achieved. Also, smaller particles are shielded by larger particles.

These factors combine to allow intermediate-sized particles to be removed and a coarse armor to develop over the finer particles, as shown in Figure 3-17. Once armoring is achieved on gravel bars in rivers, a process known as *structural strengthening* occurs (White and Day, 1979), such that a stronger current is required to transport the material available (at least one-fourth greater). It is assumed that the same type of structural strengthening occurs on armored beaches.

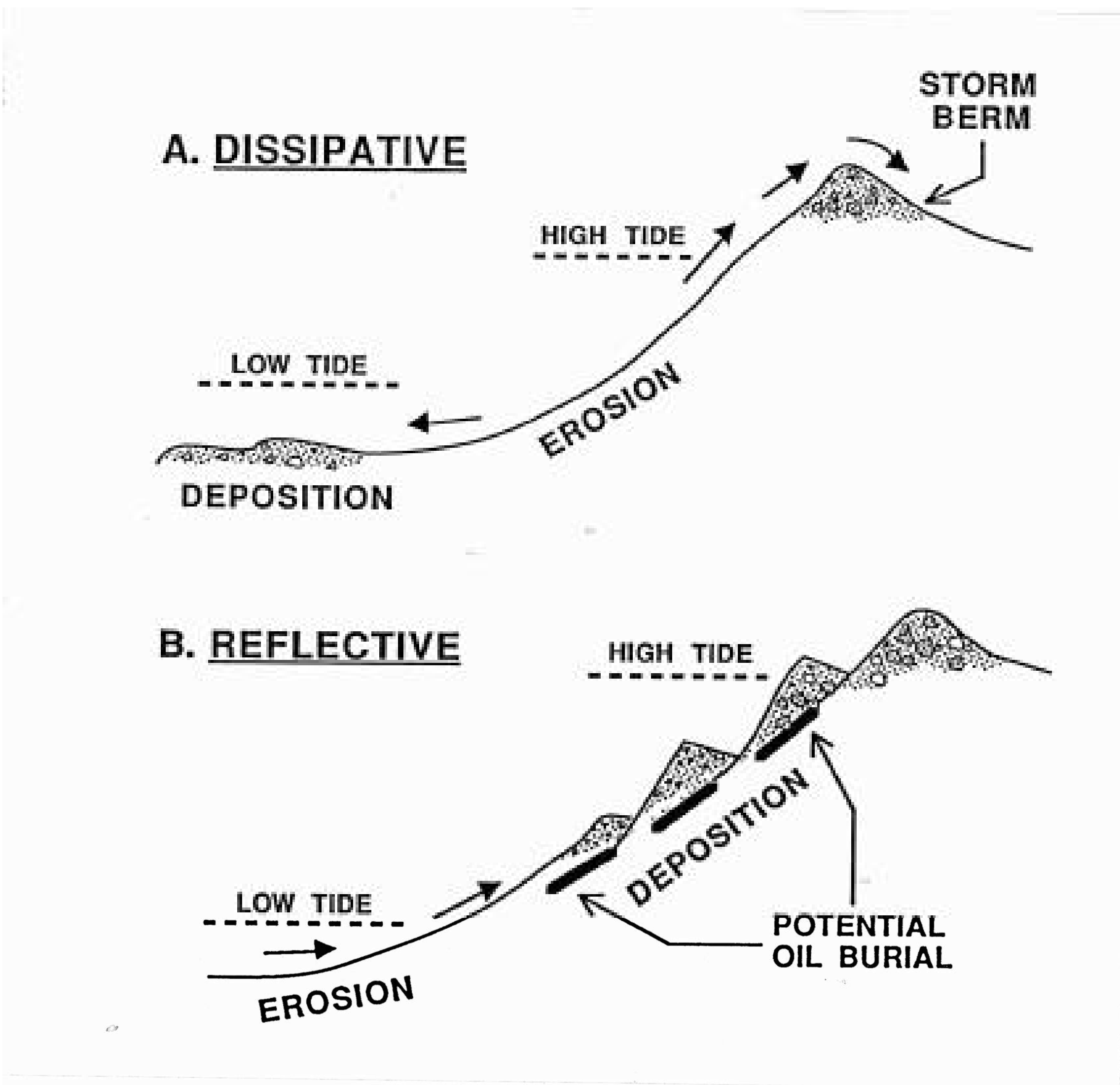


Figure 3-15. Examples of types of changes in morphology at the same gravel beach during dissipative and reflective wave conditions. Dissipative waves prevail during storms, and reflective waves are present during calmer periods on gravel beaches of this type. Note sites of potential oil burial at base of post-storm, constructional berms, a process observed at the *Exxon Valdez* spill site. (From Hayes et al., 1991; Fig. 2.)

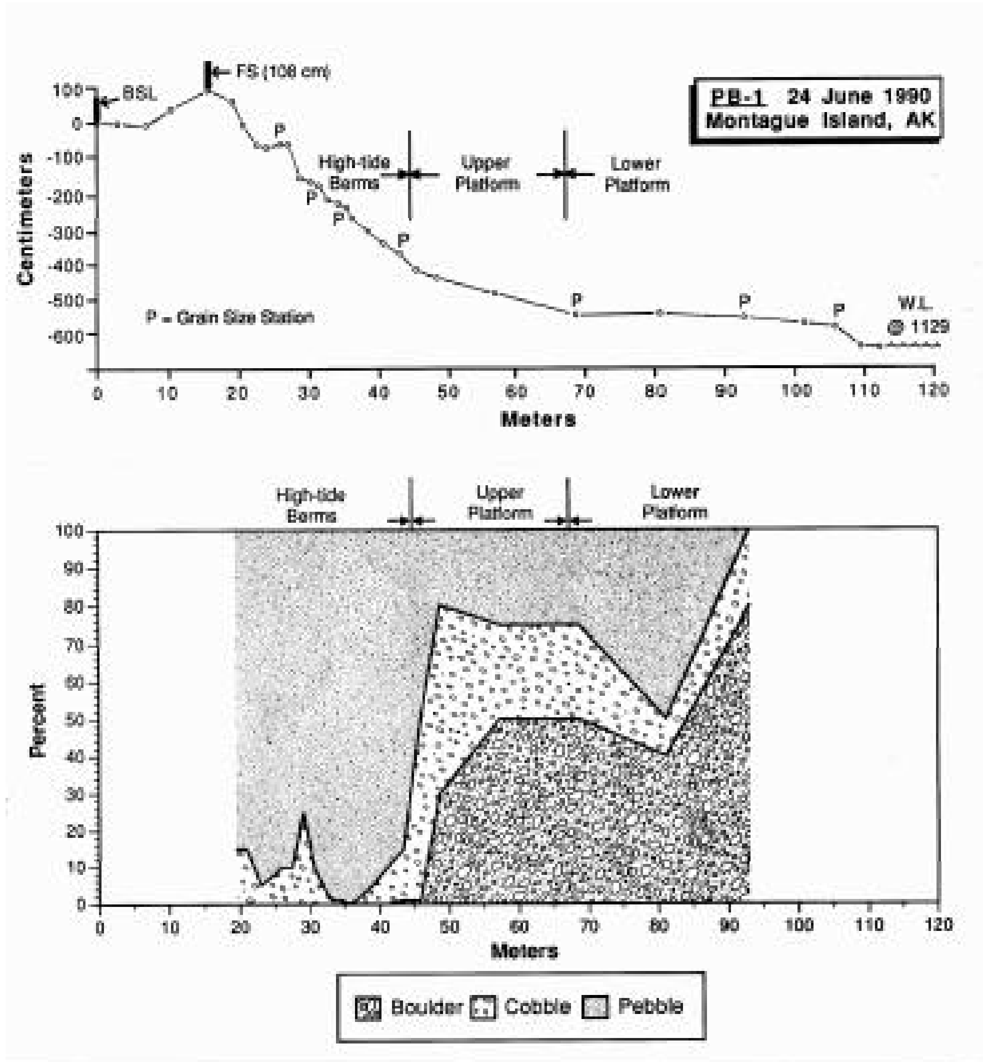


Figure 3-16. Beach profile and distribution of surface sediments for profile PB-1, on the outer coast of Montague Island, Alaska. This profile, measured at low tide on 24 June 1990, is typical of exposed, high-energy gravel beaches in an eroding, retreating setting. This area, which was subject to more than three meters of uplift in the March 1964 earthquake, has readjusted rapidly because of the constant reworking of the beach by large waves. (From Hayes et al., 1991; Fig. 3.)

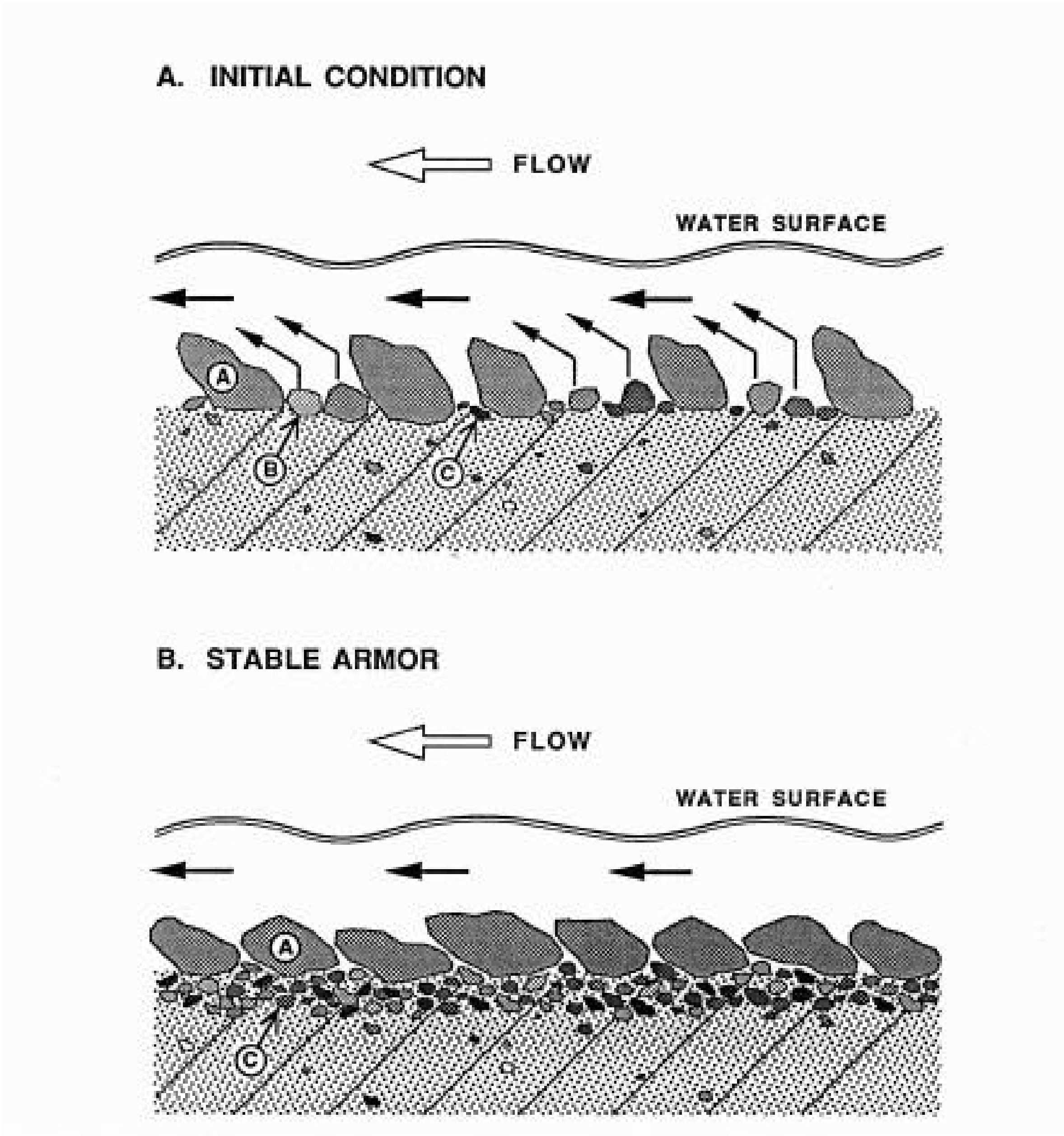


Figure 3-17. Process involved in the development of an armored surface of coarse material on a gravel beach. The particles of size A are too large to be removed by prevailing currents, those of size B are readily transportable, and those of size C are sheltered by the larger particles and are not picked up by the current. The C particles are on the order of 1 1/2 to 3 times smaller than the A particles. (From Hayes et al., 1991; Fig. 7.)

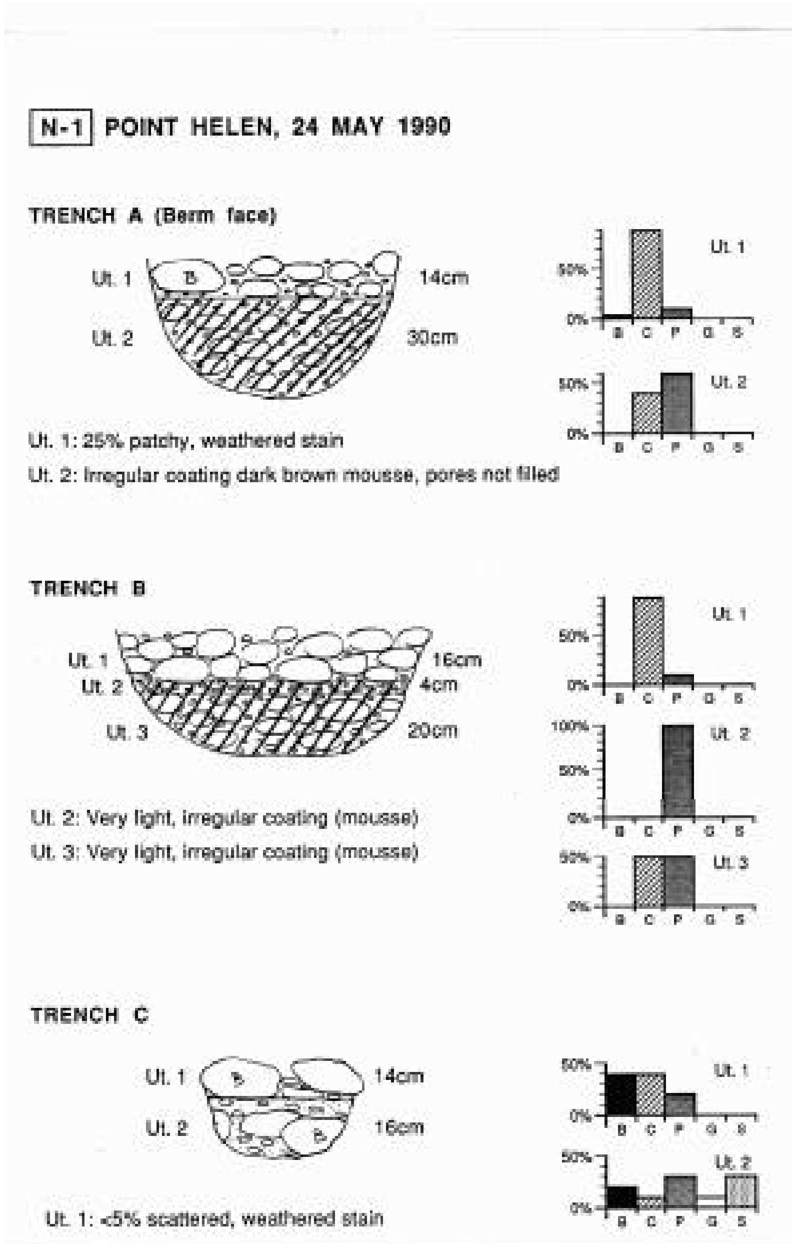


Figure 3-18. Examples of armoring on the beach at Point Helen, Prince William Sound, Alaska, on 24 May 1990. Oil from the *Exxon Valdez* spill occurred underneath the armor in trenches A and B. (From Hayes et al., 1991; Fig. 8.)

Many of the beaches in Alaska are armored, especially on the platforms. The trenches illustrated in Figure 3-18 for an armored beach oiled by the *Exxon Valdez* spill demonstrate how subsurface oil is protected below the coarse armor. The surface sediments, mostly cobbles, are clean, but the pebble-dominated subsurface sediments were still oiled, over a year after the spill. Oil beneath an armored surface would tend to remain for a longer period of time than oil buried on an unarmored beach, because of the higher velocities required to mobilize the armor. Thus, the stable armor shelters subsurface oil from natural removal. For example, on a well-armored Alaskan gravel beach, sediments at depths greater than 25 cm contained 10,000 to 18,000 ppm total petroleum hydrocarbons (TPH) in January 1991, nearly two years after the *Exxon Valdez* oil spill (Michel and Hayes, 1991).

Oil Behavior on Gravel Beaches. A number of special features of gravel beaches enhance oil accumulation and preservation during an oil spill. The major ones are:

1) *They have high porosity and permeability that allow deep penetration from the surface.* At the *Urquiola* spill, fresh oil readily penetrated up to 65 cm in gravel beaches (Fig. 3-7). At the *Exxon Valdez* spill, the oil had formed a thick mousse which piled up heavily on the beaches at first, when the cold temperatures kept the viscosity high. However, as the days warmed, the oil, which had been pooled in places on the surface, literally melted into the beach. The deepest penetration observed was 125 cm along the banks of a small stream, although the average depth of penetration was around 50 cm. After such oil penetration, the issue becomes one of predicting if and when natural processes will remove the subsurface oil.

2) *They have a high potential for oil burial by accretional features.* Gravel tends to be highly mobilized during peak and waning periods of storm activity. The finer gravel classes, such as granules, pebbles, and small cobbles, are readily moved by normal wave activity. The gravel may be moved onto the beach, in the form of berms or swash bars (Figs. 3-15B and 19A), or parallel to the beach, in the form of rhythmic topography (Fig. 3-19B). One of the biggest cleanup issues of the second year of the *Exxon Valdez* spill was what to do about deeply buried oil on the Barren Islands, where large seabird nesting colonies occur. Berm accretion had buried a layer of oil over a meter deep in a gravel beach hundreds of meters long. Later erosion would surely release the oil, but no one could be sure when and under what conditions.

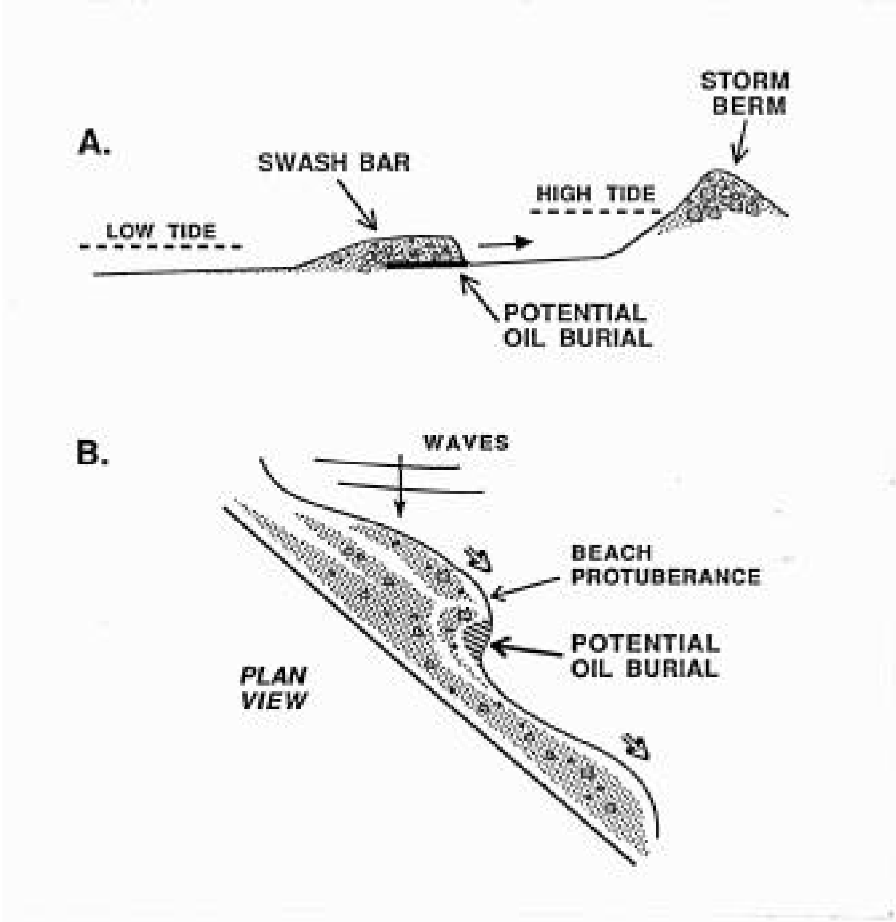


Figure 3-19. Two types of potential oil burial at permanently dissipative gravel beaches. In both examples, a mass of sediment in motion buries oil deposited at an earlier time. Oil burial by migrating rhythmic topography (B) was observed at the *Metula* spill site, and oil burial by migrating swash bars (A) was observed at the *Exxon Valdez* spill site. (From Hayes et al., 1991; Fig. 1.)

3) *The formation of asphalt pavements in sheltered areas is likely where accumulations are heavy.* Shorelines with gravel beaches tend to be irregular in outline, and sheltering from wave action is common. Even on generally exposed beaches, there can be microenvironments where oil tends to accumulate, persist, and form pavements: in the lee of larger boulders, on tombolos, and in the wave shadow of exposed headlands. At the *Arrow* spill site in Chedabucto Bay, Nova

Scotia, stranded bunker C oil remained as scattered patches of pavement 20 years later (David Kennedy, pers. comm.). During the 1991 multi-agency shoreline survey of the *Exxon Valdez* spill site, small amounts of asphalt pavement could be found on nearly every gravel beach in Prince William Sound that had been heavily oiled.

Because of these factors, gravel beaches pose very difficult cleanup problems. The rate of replenishment of gravel is usually very slow, and therefore cleanup by gravel removal can increase beach and cliff erosion where it is already a problem. Owens (1971) plotted multiple beach profiles at sites in Chedabucto Bay (the *Arrow* spill) where machinery was used to excavate oiled layers in gravel beaches over 1.5 m deep. He showed that, on beaches of limited sediment supply, removal of sediment caused erosion which was not replenished before the beginning of winter storms.

Mixed Sand and Gravel Beaches

As might be expected, mixed sand and gravel beaches have properties of both sand and pure gravel beaches. Because of the mixed sediment sizes, there can be distinct zones of sand, pebbles, or cobbles. For example, the berm is frequently composed of pebbles, surficial patches or stringers of sand can develop on the middle beachface, and cobbles usually dominate the lower beachface. The sand fraction can be quite mobile, and oil behavior is much like on a sand beach if the sand fraction exceeds about 40 percent.

Mixed sand and gravel beaches are irregular in outline, with rocky points or eroding cliffs forming headlands which provide the gravel clasts. Thus, the wave angle can be highly variable and rhythmic topography is common, with the associated potential for burial of oil by alongshore sediment movement. The gravel component can range widely in size and mobility, from highly mobile pebbles which form multiple berms, to large cobbles and boulders, which have very low sediment mobility and form a stable substrate over which the finer materials migrate.

Exposure of mixed sand and gravel beaches to significant wave activity can be episodic, particularly in places like Puget Sound where narrow channels and complex local topography limit fetch and wave height. Persistence of oil on these more sheltered beaches will be higher and natural removal processes will be less effective.

Because of sediment mobility and dessication, biological communities in mixed sand and gravel beaches are usually depauperate. The lower intertidal zone has the most epifauna (on the larger cobbles and boulders) and infauna.

The degree of oil penetration in mixed beaches is less than in gravel beaches, because the finer fractions fill the spaces between the gravel to some degree, although this is highly variable. Burial of oil is more likely on mixed beaches, and this oil can remain buried for long periods, up to years. One of the best examples of oil persistence in mixed beaches was observed at the *Metula* spill, which occurred in 1974 in the Strait of Magellan (Hayes and Gundlach, 1975; Blount, 1978; Gundlach et al., 1982; Owens et al., 1987). The majority of the shoreline impacted by the *Metula* consisted of mixed sand and gravel beaches, including a wide range of grain sizes and wave exposure. There was no cleanup of any shoreline.

Table 3-1 summarizes the observations made 1-2 years and then 6.5 years post-spill at selected locations at the *Metula* spill site. Within 1-2 years after the spill, **exposed beaches** still retained oil in two areas:

1) A band of both surface and subsurface oil along the upper beachface and above the highest berm crest

2) A layer of asphalted sediments on the low-tide terrace

The middle section of the beachface was free of oil on all exposed beaches. The subsurface oil remained soft and mousse-like in consistency. On the low-tide terrace, thick asphalted sediments ranged in width from 10-100 m. By 6.5 years, oil along the upper beachface had been reduced to a few layers, and oil on the low-tide terrace had been eroded from all but two stations, which had high currents but low wave activity. Figure 3-20 shows comparative profiles of a heavily oiled, mixed sand and gravel beach, where oil remained on the upper beachface. After 12 years, pavements 0.5 - 1 m in width and 50 to 100 m in length remained on the highest parts of the beaches. The consistency of the pavements ranged from soft to hard.

The persistence of oil on **sheltered** mixed sand and gravel beaches at the *Metula* site was much different. One to two years after the spill, field teams observed that:

1) Extensive pavements of asphalted sediments (up to 100 m wide and 700 m long) extended from the high-tide line to the toe of the beach

Table 3-1. Summary of observations at stations revisited during the 1981 survey of the *Metula* spill site. Oil was most prevalent at stations 3, 4, and 6—all located along the more sheltered First Narrows area. (From Gundlach et al., 1982.)

Station number and location	1975/1976 Survey *	1981 Survey
1 Punta Remo	A band of surface oil, 3 m wide, is evident along the upper beach face. Buried, oiled sediment extends under the surface layer for an additional 16 m seaward. Mousse is evident around the bottom edges of many cobbles on the low-tide terrace.	Oil is limited to an oiled-sediment layer, 6.2 m wide, buried 5–20 cm along the upper beach face. The middle to lower beach face and the entire low-tide terrace are free of oil.
2 Punta Baxa	Scattered oily debris is evident along the upper high-tide swash lines. Buried, oiled sediment extends for 12 m along the upper beach face. A layer of asphalted sediment, 35 m wide and 15 cm thick, is located along the upper portions of the low-tide terrace.	METULA oil remains visible as oil-clumped sand along the beach face, and as small scattered patches of oiled-sediment pavement on the low-tide terrace. The lower portion of the low-tide terrace now supports extensive mussel beds.
3 Puerto Espora spit and tidal flat	Very extensive beds of asphalted sediment are located along the interior of the embayment (20–40 m wide) and along the outer, gently sloping beach face (up to 100 m wide).	The interior and exterior zones of asphalted pavement show only minor patchy signs of erosion, particularly along the upper edges.
4 Espora marsh	Consists of a very heavily oiled marsh (18 ha) and a smaller, sheltered tidal flat (3 ha). Marsh plants are dominated by *Salicornia ambigua* and *Suaeda argentinensis*. Almost all flora and fauna within the heavily impacted zone are killed. An additional 23 ha was lightly oiled but killed most of the resident *Suaeda*.	The marsh shows only minor signs of recovery, particularly a 10–30 cm regrowth of *Salicornia* along the upper oiled fringe.
	Along the active mixed sand and gravel beach in front of the marsh, a buried, oiled-sediment layer, 35 cm thick, extends for 16 m along the upper beach face.	Buried, oiled sediment, now composed of hard asphalt, remains present along 2.5 m of the upper berm.
	To the west of this station, a zone of asphalted sediment, 15–20 cm thick and 100 m wide, extends along the upper low-tide terrace.	A zone of asphalted pavement, 90–100 m wide, remains along the upper low-tide terrace.
6 Punta Espora	Tar balls are common along the upper swash lines and oil-stained cobbles appear across much of the beach face. Extensive deposits of asphalted sediment intermittently appear as pockets of clean gravel migrate from west to east along the beach.	Asphalted sediment still remains, having a maximum dimension of 40 m × 5 m and a thickness of 15 cm. No other METULA oil is present; however, some light, oily swashes of recently spilled oil are common along the upper beach face.
7 Cabo Orange	Oil-stained gravel is common along the upper swash lines. An asphalted-sediment pavement, 20 m × 150 m, is present along the upper low-tide terrace.	No surface or buried oil remains along the beach face or low-tide terrace.
8 Punta Catalina	Consists of a washover along the Atlantic coast which has several buried, oiled-sediment layers and a surface of asphalted sediment along the crest of the upper beach face.	This site has been extensively eroded. No oil could be found.
9 Punta Catalina	Small pieces of asphalted sediment are scattered across the upper beach face (located along the west side of the spit).	No oil remains at this site.
10 Southern edge of Bahia Felipe	Pieces of asphalted sediment are present on top of the spit that fronts the area. Behind this spit, narrow discontinuous bands of asphalted sediment line the upper edges of the channel.	No oil remains on the spit; however, the narrow bands of asphalted sediment along the interior margin still persist.
11 Southeast corner of Banco Lomas tidal flat	A discontinuous band of thin oil with scattered tar balls is present along the very upper edge of this huge tidal flat.	Oil remains just as it was previously. A vehicle has driven over the site leaving tracks across the oiled area.
12 Cabo Posesion	Scattered oily debris is found along the upper swash lines.	No oil is present.
57 Punta Daniel	Scattered oil crust is found along upper berm area. Lightly scattered, oiled-sediment conglomerates are on the upper low-tide terrace.	No oil is visible.

*Annual data not available.

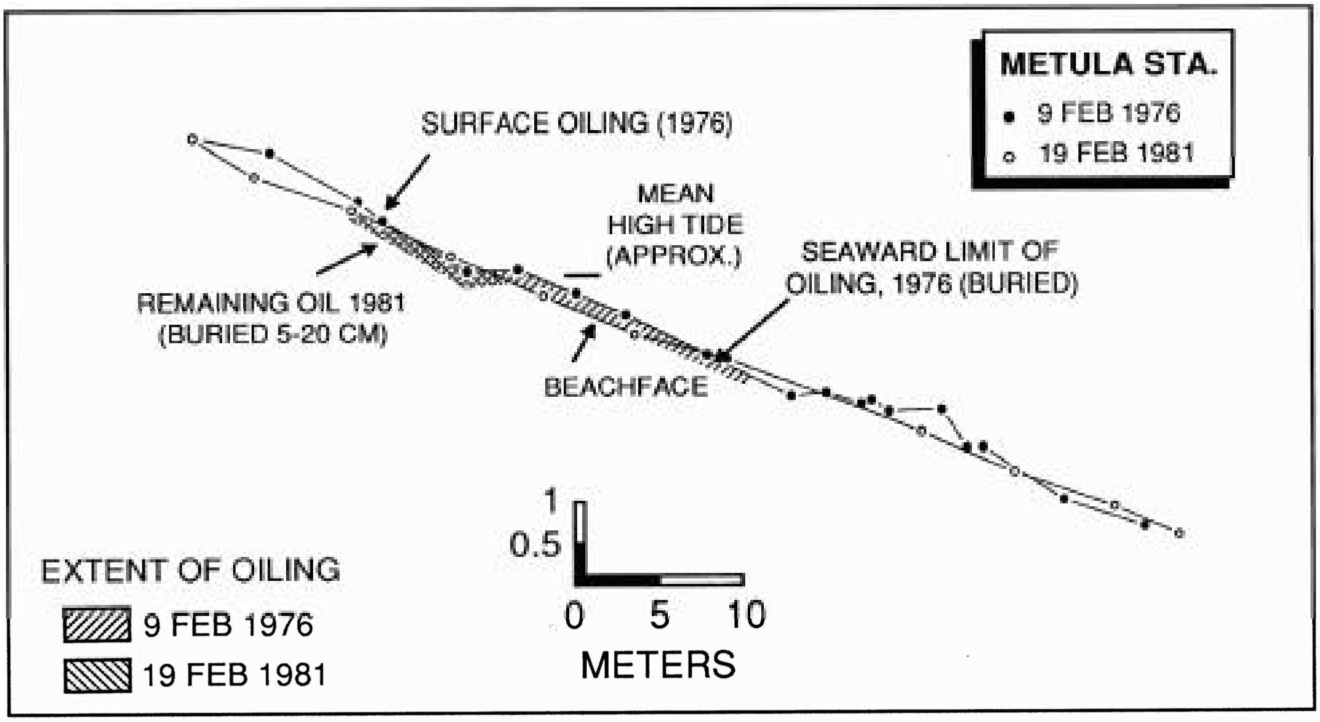


Figure 3-20. Changes in the oil distribution on a sand and gravel beach at the *Metula* spill site between 1976 and 1981 (Strait of Magellan, Chile). The surface oil present in 1976 was buried by 1981. Wave action had reworked much of the middle beachface area, removing the subsurface oil from that zone. However, 6.2 m of the original 19 m zone of oiled-sediment layers remained in place, seven years after the spill. (After Gundlach et al., 1982; Fig. 3A.)

2) Discontinuous bands and pieces of asphalted sediments were scattered throughout the intertidal zone

3) Most of the oil remained on the surface

By 6.5 years later, the extensive pavements showed only minor evidence of erosion along the upper edge of the pavement. After 12 years, there was still little change. Owens et al. (1987) reported that, at the most heavily oiled and sheltered site:

> "...oil is present: (1) in very large volumes (more than 100 m^3 in total); (2) over the entire area, which includes marsh, sheltered beach and exposed beach environments; (3) in all sections of the beach from the low-water level to the spring high-water level; and (4) generally as an apparently fresh deposit below a weathered surface crust."

The behavior and short-term impacts of oil on mixed sand and gravel beaches can be summarized as follows:

On exposed beaches:

- During small spills, oil will be deposited along and above the high-tide swash
- Large spills will spread across the entire intertidal area
- Oil penetration into the beach sediments may be up to 50 cm
- Burial of oil may be deep at and above the high-tide berm, where oil tends to persist
- Oil can be stranded on low-tide terraces composed of gravel, particularly if the oil is weathered or emulsified

On sheltered beaches:

- Pavements are likely to form wherever heavy accumulations of oil can fill the voids between the sediments
- Once formed, these pavements are very stable and can persist for many years
- Any oil stranded above the high-tide line will be highly persistant

Tidal Flats

Intertidal flats are deposits of sand and/or mud of very low slope that are exposed at low tide. The width of the flat is dependent on the tidal range and sediment supply; very wide flats are found mostly in macrotidal (TR > 4 m) areas. Tidal flats occur along shorelines sheltered from direct attack by large waves, although highly mobile sand shoals are common at the mouths of inlets. Thus, compared to beaches, tidal flats have slow deposition and erosion patterns.

Origin and Sedimentation Patterns

Much of the original work on the sedimentology of tidal flats was done on the shoreline of the North Sea, first by Van Straaten in the Wadden Sea, The Netherlands, and then by Reineck and colleagues on the tidal flats of Germany. Van Straaten published several summary articles (1951; 1954), and Reineck's work is summarized by Reineck and Singh (1975) and several later papers.

Through a series of detailed studies, van Straaten determined that the Wadden Sea can be subdivided into three distinct environments: the <u>marsh</u> (above mean high water level), the <u>tidal flat</u> (intertidal zone), and the <u>tide channel</u> (below mean low water level). He further subdivided the tidal flat in <u>high flats</u> (between mean high water and half tide levels) and <u>low flats</u> (between mean half tide and low water levels). The sediments of the high flats are intensely bioturbared, whereas those of the lower flats contain mostly physical sedimentary structures, such as ripple marks. These environments are illustrated in Figure 3-21, which indicates that the main trends in grain-size distribution in the Wadden Sea show a systematic decrease of mean size of sand and silt particles and an increase in clay content from the tidal inlets toward the estuary shores. The coarsest sediments are thus found on the bottom of the largest tidal inlets and the finest on the highest reaches of the tidal flats. The same pattern occurs on many other coastlines of the world, for example the mesotidal components of the coasts of South Carolina/Georgia, Alaska, California, and Puget Sound.

The problem of why large quantities of mud accumulate on the upper reaches of the tidal flat is an interesting one. Van Straaten and Kuenen (1957) indicated that much of this mud is deposited at ebb just before water is drawn away. Postma (1967) proposed that a combination of <u>settling lag</u> and <u>scour lag</u> moves fine-grained

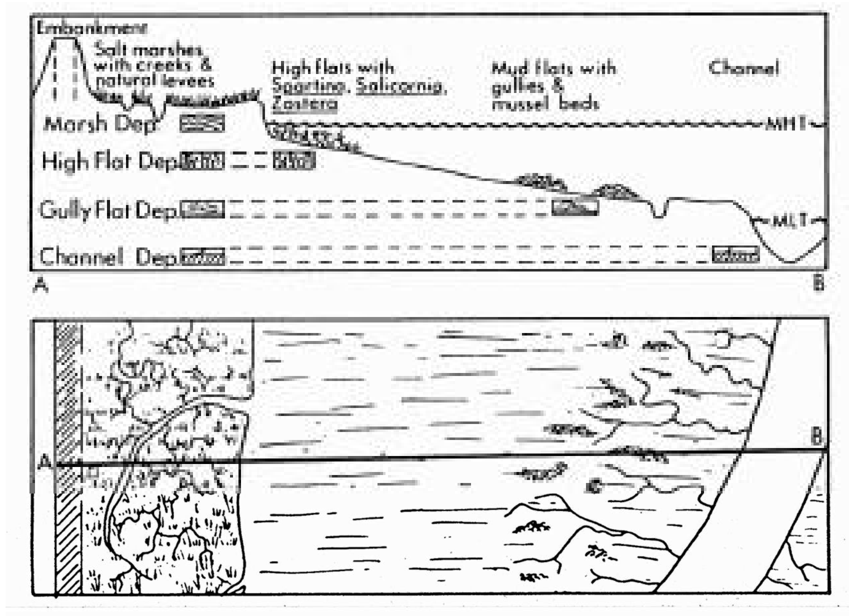


Figure 3-21. Sheltered tidal flat region of the Wadden Sea, The Netherlands. (After Van Straaten, 1951.)

sediments up into the estuary. These processes, which are shown diagrammatically in Figure 3-22, were described as follows by Nichols and Biggs (1985; p. 138):

> "*Settling lag effect*. The diagram ..(in Fig. 1-22).. shows the velocities with which different water masses move with the tides at each point along a section through a tidal inlet (left) to the shore (right). Although the tide at fixed points is assumed to be symmetrical, the distance-velocity curves are asymmetrical. A water mass moves in and out along one such curve. The tangent (P) represents the maximum current velocity in each point and meets each curve at a point attained by the water mass at half tide. The curves apply only to idealized average conditions, and scour lag is neglected.
>
> A particle at point 1 is taken into suspension by a flood current (water mass at A) of increasing velocity and starts to settle toward the bottom at point C, when the current still has a velocity equal to 2. While settling, the particle is carried farther inland by the still flooding currents and reaches the bottom at point 5 while the water has a velocity at point 4.

Scour lag effect. After the turn of the tide, the particle cannot be eroded by the same water mass (AA′) because this water parcel attains the required velocity later at a point beyond the particle toward the inlet. The sediment particle is therefore eroded by a more landward water mass (B′) and is transported toward the inlet to point B. At 7, it starts to drop out of suspension and reaches the bottom at point 9. During one tidal cycle, the particle has therefore been transported landward from point 1 to 9. After a number of these landward transport cycles, the particle may reach a point where it cannot be entrained by subsequent ebb flow currents because of the landward decrease of the average velocity of the tidal current (after Postma, 1967, and Van Straaten and Kuenen, 1957)."

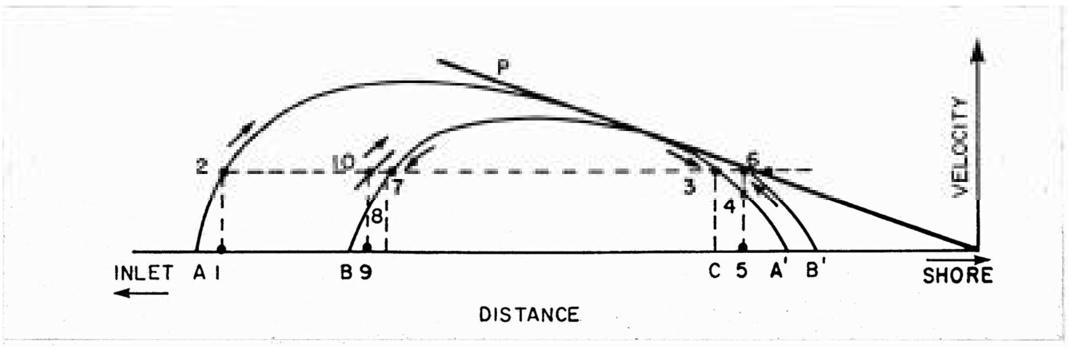


Figure 3-22. Diagram of the settling lag and scour lag effect in estuaries as described by Postma. (From Nichols and Biggs, 1985; Fig. 2-39.)

Eventually, the fine sediments reach the tidal flats.

Flocculation and aggregation of suspended silts and clays is another process that aids in the buildup of muddy sediments in estuaries (and ultimately on tidal flats). Examples of sizes and groups of flocculated particles are given in Figure 3-23.

In order for flocculation to occur, the suspended particles must be brought together (i.e., collide) and stay together (i.e., cohere). Collision is enhanced in waters with large volumes of suspended sediments, and the natural forces that tend to repluse fine particles from each other are destabilized by high concentrations of cations,

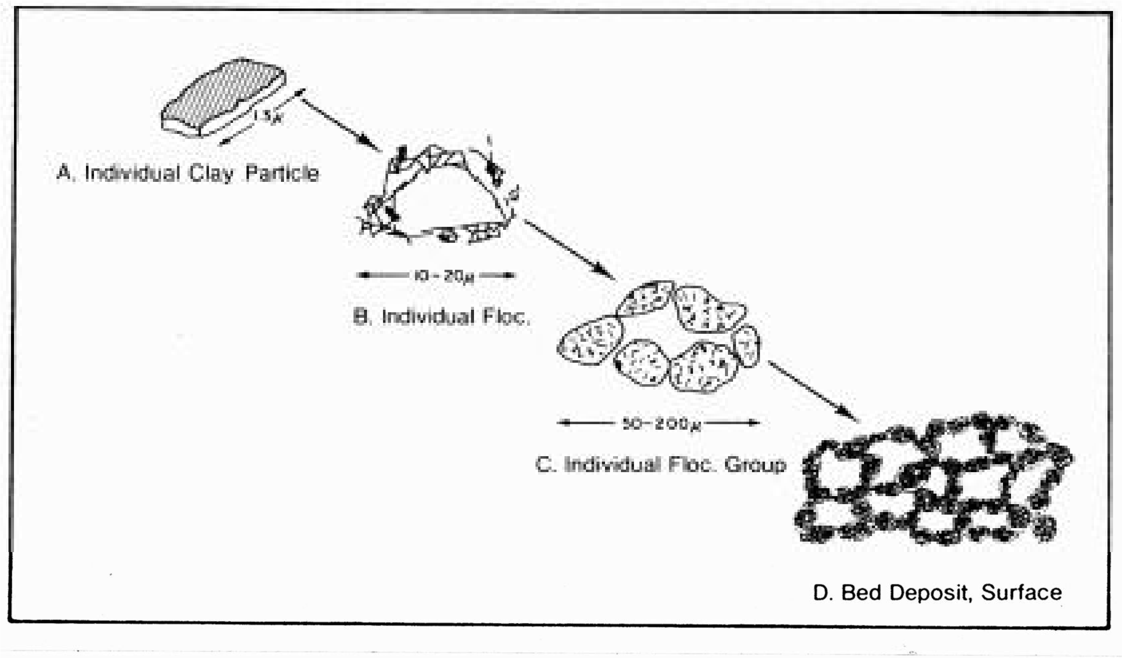


Figure 3-23. Schematic sequence of typical structures and size of flocculated fine sediments (flocs) and groups of flocs. (From Nichols and Biggs, 1985; Fig. 2-41.)

such as Ca++, Mg++, and Na+ (Nichols and Biggs, 1985). Both of these conditions are met in estuaries, where sediment-laden stream waters mix with the "salt wedge" of marine water that moves into the estuary on a rising tide.

Once the mud is deposited on a tidal flat, it tends to remain there because:

1) The mud dries out.

2) Burrowing organisms tend to stabilize the mud.

3) Diatoms move up through the mud and deposit slime.

4) Much higher velocities are required to <u>erode</u> consolidated mud than those at which it was <u>deposited</u>, as illustrated by the diagram in Figure 3-24.

In some instances, mud is trapped between plants on the flat. Another factor of prime importance to mud deposition is the super-abundance of the suspension-feeding organisms on the flats, such as oysters and clams. During the filtering process, these organisms compress the finely divided clay particles and bind them together in their intestines as fecal pellets. Another part of the suspended matter is

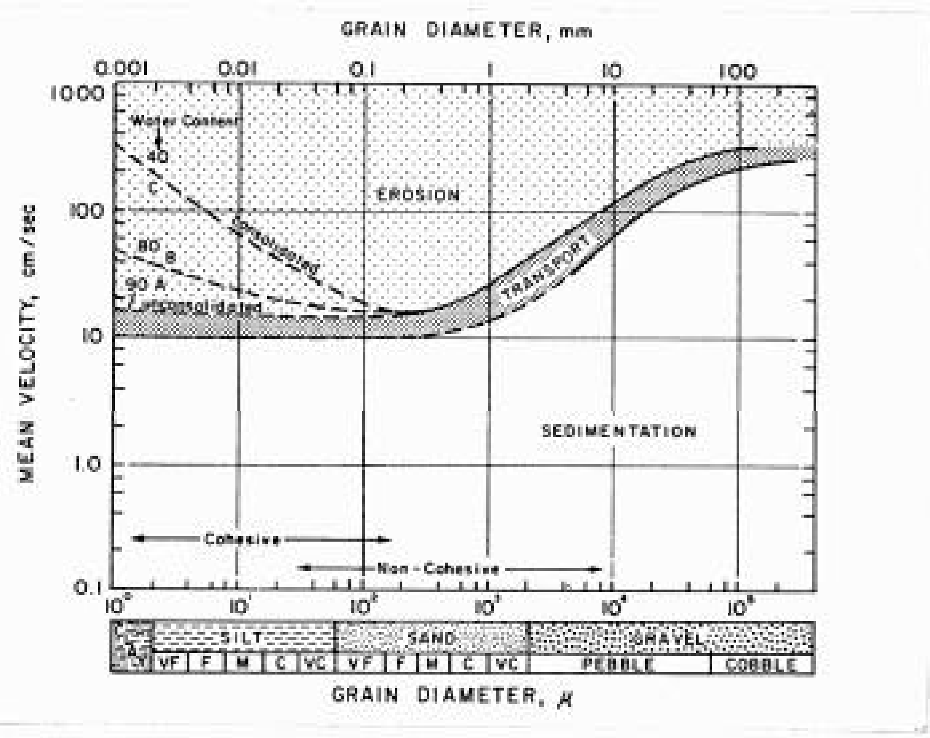


Figure 3-24. Sediment erosion, transport, and deposition regimes for mean current velocities versus grain size. Solid lines represent critical velocities required for erosion, transport, and deposition of bed sediment while dashed lines represent extrapolated trends. Lines A-C are critical velocities for various stages of consolidation represented by decreasing water content. Adapted from Hjulstrom (1939) and Postma (1967); by Nichols and Biggs (1985; Fig. 2-17).

coagulated in their gills and pushed back into the water as pseudo-feces. These feces and pseudo-feces are easily deposited, even in comparatively turbulent water (Van Straaten and Keunen, 1957). This process of mud accumulation is clearly evident around the oyster mounds on the tidal flats of the South Carolina coast (Hayes and Sexton, 1989).

For oil-spill planning, tidal flats are divided into two types: exposed and sheltered.

Exposed Tidal Flats

Exposed tidal flats can be characterized as follows:

- They are composed primarily of sand and mud (silt and clay), though in Alaska they can have a large gravel component

- The presence of sand indicates that tidal or wind-driven currents and waves are strong enough to mobilize the substrate

- They are always associated with another shoreline type on the landward side of the flat

- There may be low sand ridges slowly migrating over the flat surface

- The sediments are water-saturated, with only the topographically higher ridges and bedforms drying out during low tide

- The sediments are compact and may support pedestrian and vehicular traffic in some areas

- Biological utilization can be very high, with varying numbers of bivalves, macroinvertebrates, and polychaetes

- Birds utilize exposed flats as roosting and foraging areas

The behavior of oil on exposed tidal flats has been studied at several major spills. At the *Metula* site, oil slicks moved across wide flats (up to 10 km wide) and accumulated only at the landward edge of the flat (Blount, 1978). The oil remained on the surface, penetrating only a few centimeters, and there was no burial after 1.5 years. Because the wide flats attenuate nearly all the wave energy, the oil eventually formed into a thin pavement or crust which remained unchanged for 6.5 years. At the *Urquiola* spill, oil was observed to pass over the flats and accumulate on the adjoining beach. At low tide, heavy oil slicks covered the flat, but the rising tide would lift the oil off and push it across the flat. No long-term deposition of oil on the flats was observed, although the surface sediments were lightly stained early in the spill. Biological impacts were significant, with over 70 percent mortality of cockles. At the *Amoco Cadiz* spill, heavy oil slicks passed across the flats; oiled sediments occurred on the tidal flats only where cleanup crews had dug trenches and pits for oil collection. Where high densities of bivalves occupied the flats, there were mass mortalities.

The only spill where significant contamination of exposed tidal flats has been reported is along the Saudi Arabian coast where the Gulf oil spill innudated the shoreline for 500 km. The oil coverage on the tidal flats was nearly 100 percent, as of May 1991. This spill was unique in that onshore winds kept extremely large slicks piled up against the shoreline for months. Eventually, the oil adhered to the intertidal sediments. But, the oil did not penetrate the sediments very deeply; in most cases, the oil was less than 5 cm deep, with a thin surface oil crust (Michel, 1991). Also, the oil did not completely fill the pore spaces, a condition that tends to result in formation of asphalt pavements, which would slow natural removal rates. Instead, the oiled sandy sediments showed permeability to water, which should speed removal by flushing and weathering by degradation. The surface crust had been ripped up and flipped over in some places, indicating that the flats were being exposed to tidal current energy. Tidal currents draining off the wide flats were generating enough energy to lift the oil crust and mobilize the sediments, providing an important "self-cleansing" mechanism.

Based on observations at many spills, the behavior of oil on exposed tidal flats can be summarized as follows:

- Oil does not usually adhere to the surface of exposed tidal flats, but rather moves across the flat and accumulates at the high-tide line
- Heavy accumulations will cover the flat at low tide
- Oil does not penetrate the water-saturated sediments
- Biological impacts can be severe, primarily to infauna, thereby reducing food sources for birds and other predators

Sheltered Tidal Flats

Sheltered tidal flats can be characterized as follows:

- They are composed primarily of silt and clay
- The sediments are very soft and cannot support even light foot traffic
- Wave energy is very low, although there may be strong tidal currents active on parts of the flat and in channels across the flat
- They are usually fronted by marshes
- They have a dense and diverse infauna, which is highly utilized by birds

Sedimentation on sheltered tidal flats results from deposition of sediment from suspension, which occurs primarily during periods of slack high water. The upper tidal flat is a zone of higher rates of accumulation of finer-grained material due to "differential time of inundation and submergence ...during a tidal cycle, associated changes in bottom-current velocities of tidal currents during a tidal cycle (being therefore concentrated over the low-tidal flats), and the dominance of suspension processes near the time of high tide and slack water, which favors preservation of mud in high-tidal flats." (Klein, 1985). The processes of flocculation and scour/settling lag, described above, are also important in the partitioning of sediment sizes along sheltered tidal flats.

Sheltered tidal flats become contaminated by direct contact with oil slicks and by deposition of contaminated suspended sediments. During the *Amoco Cadiz* spill, large waves dispersed the oil into the water column, both as the oil exited the ship and when storm waves eroded the oil from exposed beaches. During the first three weeks, about 20,000 metric tons of oil were estimated to be incorporated into the water column (Gundlach et al., 1983). This oil sorbed onto suspended sediments which were then deposited onto sheltered tidal flats; oiled intertidal sediments were found in sheltered bays which never received any surface slicks. Oil removal and weathering rates were slowest in very fine-grained sediments.

Based on observations at many spills, the behavior of oil on sheltered tidal flats can be summarized as follows:

- Oil does not usually adhere to the surface of sheltered tidal flats, but rather moves across the flat and accumulates at the high-tide line
- Very heavy accumulations will cover the flat at low tide
- Oil will not penetrate the water-saturated sediments at all
- In areas of high suspended sediments, sorption of oil can result in contaminated sediments that can be deposited on the flats
- When sediments are contaminated, oil will persist for years
- Biological impacts can be severe

Sheltered Rocky Coasts

Sheltered rocky coasts encompass many types and sizes of substrates. Included in this general class are:

- Vertical bedrock cliffs, such as along fjords
- Wide, rocky ledges which may be strewn with boulders

- Rocky, rubble slopes which are formed by passive accumulation of sand to boulder-sized talus on bedrock slopes

The only common factors among these diverse shoreline types are a hard substrate and the absence of significant wave or tidal energy. Otherwise, there can be wide variations in the width of the intertidal zone and the degree of "permeability" of the rocky substrate. Because of the low wave energy, there is little sorting of sediments, so the substrate is a jumbled mix of grain sizes, from boulders to clay. This poorly sorted mixture usually does not allow deep penetration of oil into the subsurface. But, then, where is the “surface” on a shoreline with boulder- and cobble-sized rubble layer overlying an irregular bedrock platform with patches of muddy sand and granules?

Without substrate mobility, the hard, rocky surface can be heavily colonized by a rich epifaunal community in the mid to lower intertidal zone, including algae, mollusks, and snails. On steep, sheltered bedrock shores, the intertidal zone can be nearly vertical; zonation patterns for attached epifauna have sharp boundaries because of the lack of waves to smear the zones over a wider area. Tidal pool communities are uncommon and small. Concrete seawalls are the man-made equivalents of this shoreline type.

Oil tends to readily adhere to the dry rock surface, particularly along the high-tide line where there are little to no attached organisms and the rock dries for longer periods. During the *Exxon Valdez* spill, many miles of sheltered vertical bedrock shores were heavily oiled in this manner. Only infrequently did oiling of the mid to lower intertidal zone occur. It seems that oil did not adhere to the wetter, heavily colonized surface of the lower half of the intertidal zone, but rather the oil lifted off these surfaces with the rising tide.

On sheltered, *vertical rocky shores*, oil will:

- Adhere readily to the rough rocky surface, particularly along the high tide, forming a distinct oil band
- The lower half of the rock face usually stays wet enough to prevent oil from adhering and remaining
- Heavy oils and weathered oils can cover with upper zone with little impacts to the rich biological communities of the lower zone

- Fresh oil and light refined products have high acute toxicities which can affect attached organisms after even short exposures

On sheltered, *bedrock ledges*, the intertidal zone can be very wide. The surface can be covered with a wide range of grain sizes, but the bedrock ledge is the dominant substrate type. There can be some evidence of sorting of the sediment veneer, especially at the high-tide line where a small mixed sand and gravel beach can form. But the frequency of wave action is very low, at the most 1-2 times per year. In very sheltered settings, the rock ledge can be covered by a thin layer of weathering residue that fills in the cracks and crevices on the uneven rock surface.

Oil stranding on this shoreline type can coat the surface and penetrate this surface residue. Oil penetration will be limited by the depth of the intact bedrock surface. But it should be noted that rock fractures can be 10-20 cm deep and are common sites of oil pooling and persistence. Figure 3-25 shows a sketch, profile, and grain-size cover for a typical sheltered rocky ledge in Alaska. Note that the surface is covered by a thick layer of angular debris. The oil on this shoreline eventually formed a patchy asphalt pavement covering the upper one-third of the ledge. This specific site was not cleaned, as part of a research program to monitor the effectiveness of different treatment techniques versus natural recovery. Without any cleanup, heavy patches of oil have remained and formed pavements three years post-spill. The oil coating on the rock surfaces has dried, started to crack, and has been reduced by about 50 percent in 2.5 years. However, oil in the rock crevices and below the surface boulders has not changed at all and remains relatively fresh.

The biological utilization of these rocky ledges can be very high, with dense growth of algae and associated epifauna. Tidal pools can be common, and there can be a rich underrock community. When heavily oiled, the lower intertidal areas can be covered by oil trapped in low areas and pools on the irregular rock surface during the falling tide. If the oil is weathered and sticky, it can eventually strand, penetrating into the small accumulations of sediments on the rock surface. Seldom have we seen oil adhering to bedrock on the lower intertidal zone; the surface stays too wet and the oil is lifted off with the rising tide.

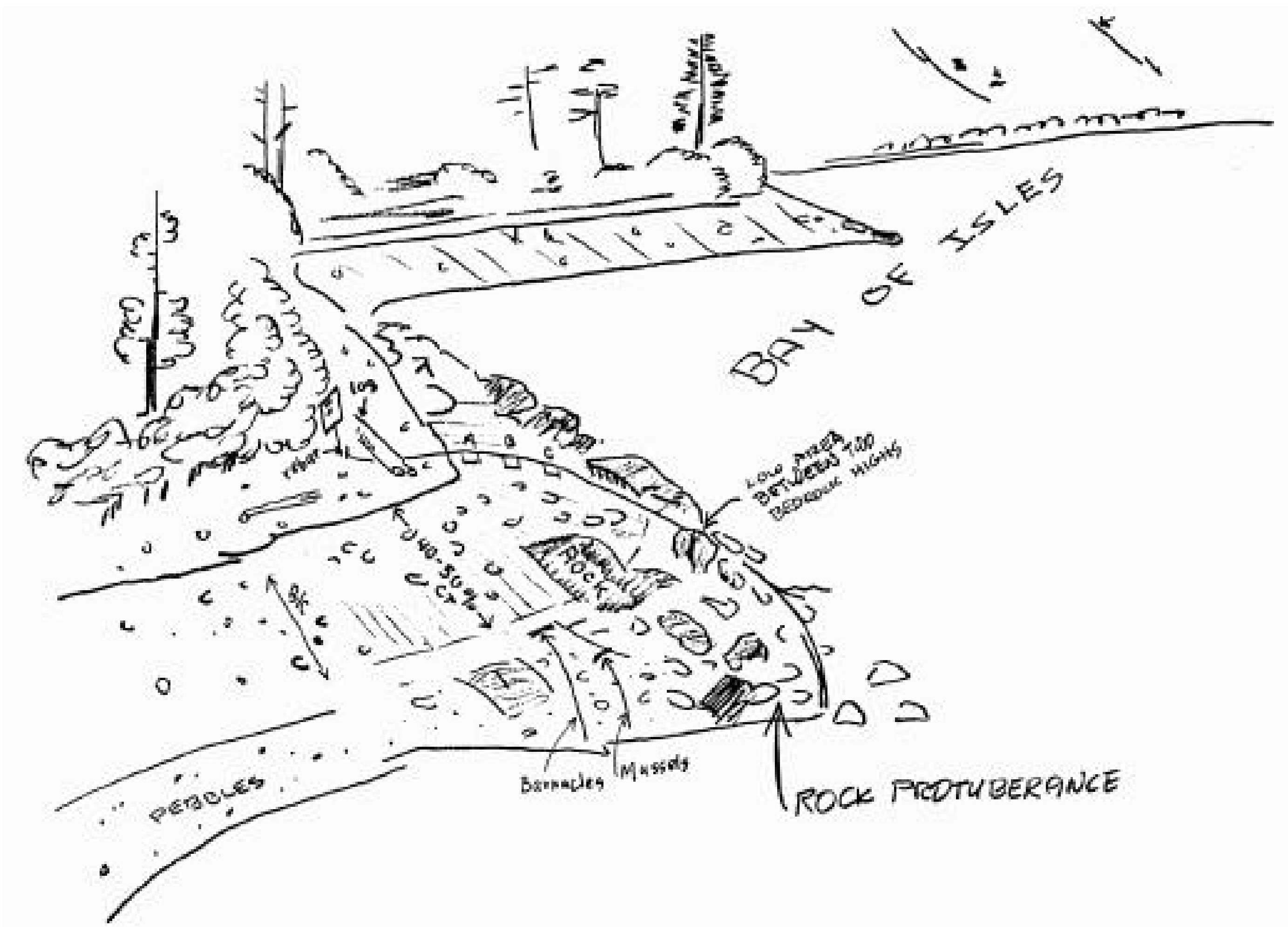


Figure 3-25. Example of a sheltered rocky ledge oiled during the *Exxon Valdez* spill, NOAA's station N-6 in the Bay of Isles, Prince William Sound. A) Beach sketch. A permanent topographic profile was run down a small draw between two bedrock highs. Note barnacle and mussel zones on lower half of the rock face.

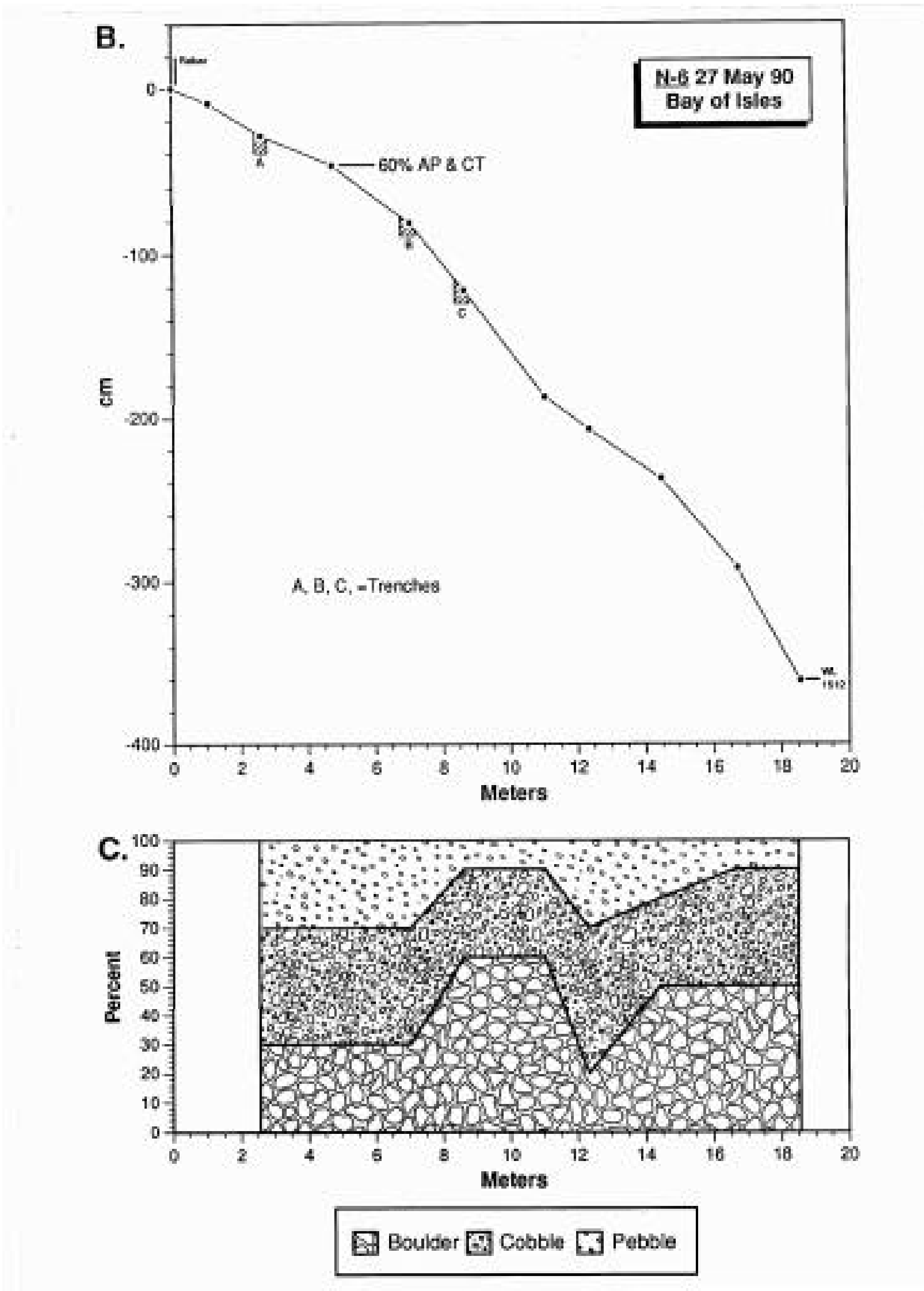


Figure 3-25. Continued. B) Topographic profile, illustrating the steepness of the profile. C) Surface sediment distribution pattern based on grain size estimates at eight of the survey points along the profile (circles shown in B). Note slight increase in size down the slope. This surficial debris is angular and poorly sorted, which indicates little transport by wave action.

On wide, *rocky ledges*, oil will:

- Adhere readily to the rough rocky surface, particularly along the high tide, forming a distinct oil band
- If a beach is present, the oil will penetrate the sediments, with long-term persistence very likely
- Fractures in the bedrock surface are sites of oil pooling and persistence
- Even for wide ledges, the lower intertidal zone usually stays wet enough to prevent oil from adhering to the rock surface
- Heavy oils and weathered oils can persist on the lower intertidal zone by penetrating surficial sediments
- Fresh oil and light refined products have high acute toxicities which can affect attached organisms after even short exposures

Sheltered *rocky rubble slopes* have the greatest potential for long-term persistence of oil. These shoreline types are relatively steep and short. The bedrock surface can be covered with a thick veneer of poorly sorted materials, which can vary greatly in degree of permeability. Figure 3-26 shows a sketch, profile, and surface oil coverage for a rubble slope from Prince William Sound, which was set aside and never cleaned. Note that the oil stranded only on the upper zone, with 100 percent coverage in September 1989, six months after the spill. By September 1990, surface oiling had been reduced to a maximum of 30 percent coverage. Again, most of the oil on the undersides of the rubble remained.

Most of the time, the subsurface is very tightly packed and the oil penetrates only the top few centimeters. Without oil removal, pavements are formed. However, on this surface can be large boulders, and oil will be deposited in the open spaces between the boulders and at the base. It is nearly impossible to cleanup this oil and natural removal rates are extremely slow.

Another problem area on these rubble slopes is where they are covered with a loose assemblage of debris, which can be very permeable. Oil pooled on these slopes can penetrate deeply, up to 50 cm. At the site shown in Figure 3-26, fresh-looking oil remained at depths of 30 cm as of September 1991, 2.5 years later. Detailed chemical analysis of the oil showed that it had weathered very little.

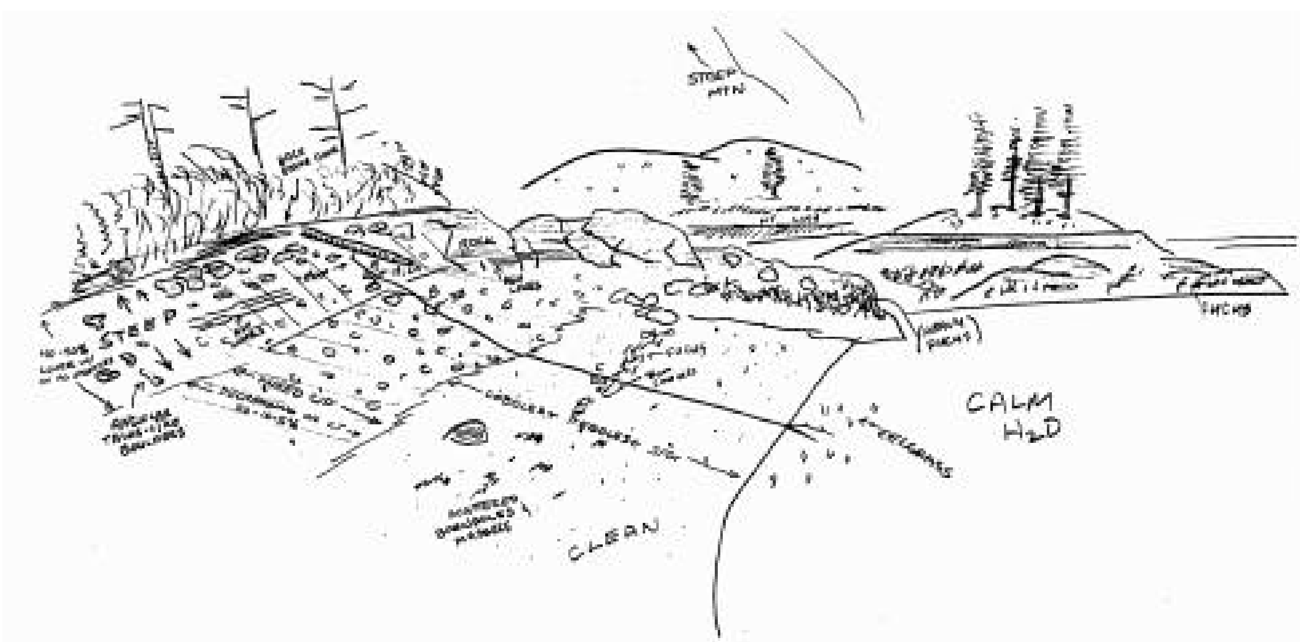


Figure 3-26. Example of a sheltered rubble slope that was oiled by the *Exxon Valdez* spill, NOAA's station N-13 in Herring Bay, Prince William Sound. A) Field sketch. The contrasting sediment types and slopes of the two subdivisions of the profile, angular talus-like material on the steep rubble slope and finer material on the flatter bay bottom, are evident. Oil cover as high as 50 percent was still present on the upper portion of the rubble slope on 27 May 1990, over one year after the spill.

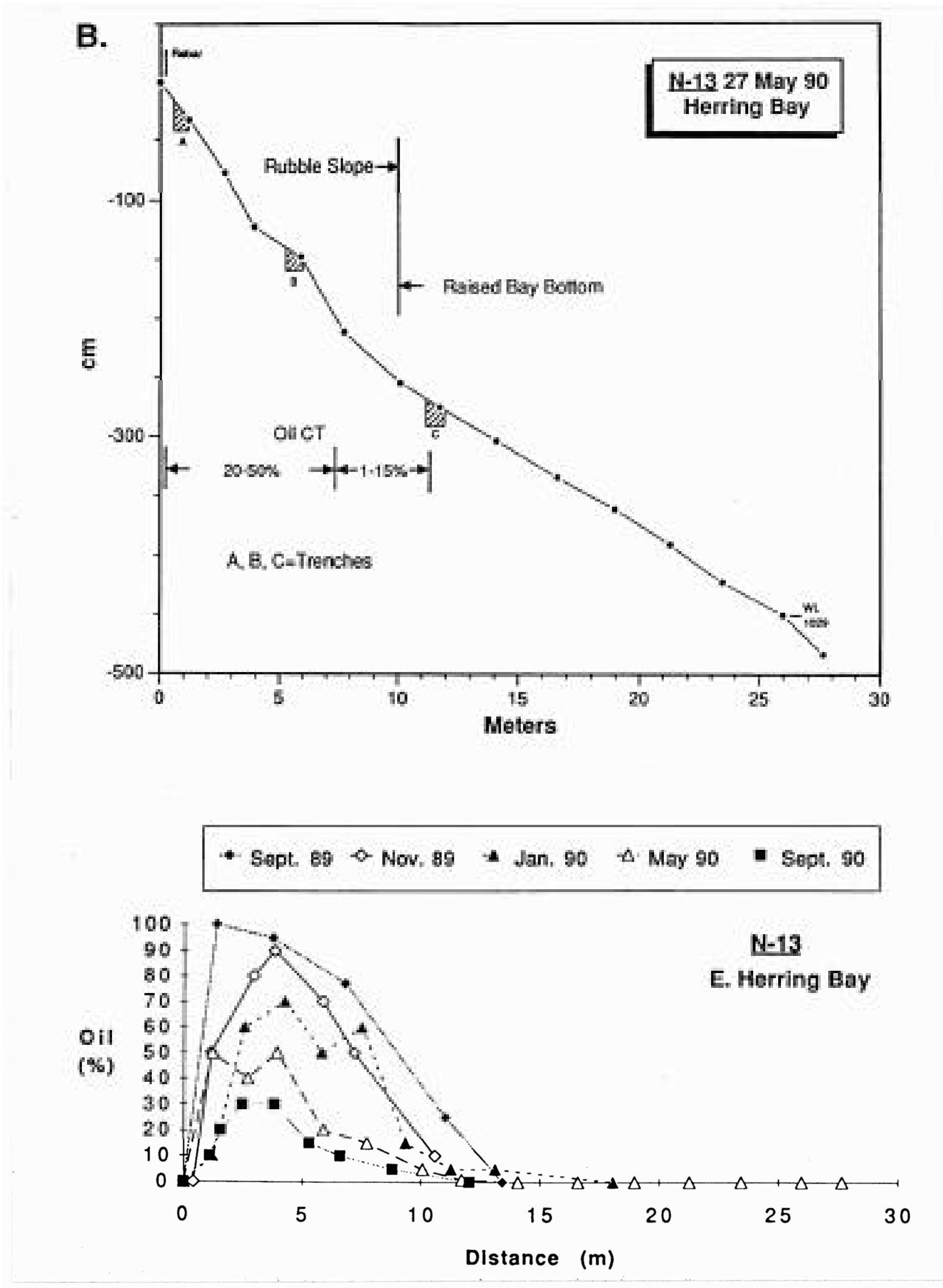


Figure 3-26. Continued. B) Topographic profile, illustrating the clear break between the rubble slope and the raised bay bottom. The distribution of oil coating (in percent) is also shown. C) Plot of the distribution of surface oil coverage between September 1989 and September 1990, based on visual estimates.

On sheltered *rubble slopes*, oil will:

- Adhere readily to the rough rocky surface, particularly along the high tide line, forming a distinct oil band
- Penetrate into the crevices formed by the surface rubble and pool at the contact of the rubble and the surface
- Form pools and eventually pavements under heavy oiling
- Penetrate deeply into loosely packed rubble, causing long-term contamination of the subsurface sediments

Marshes

Depositional shorelines sheltered from wave action have a range of intertidal and supratidal environments, from barren saline flats (sabkhahs) to mangrove forests, depending mainly on the coastal climate. Some examples are given in Figure 3-27. This discussion is limited to marshes, which, as defined here, are restricted to wetlands containing emergent, herbaceous vegetation. Thus, they include salt, brackish, and freshwater marshes. But, the emphasis in this section is on marshes bordering water bodies such as estuaries, bays, lakes, and rivers, where floating oil slicks can impact the vegetation.

Marshes of the Southeastern USA

The estuaries on the coasts of South Carolina and Georgia are host to one of the most extensive developments of salt, brackish, and freshwater marsh systems in the USA. Many excellent, detailed studies of these marshes allow them to be used as a general model of marsh ecology and sedimentation. These marshes are well documented as being the primary food source for the coastal and nearshore ecosystem of the region. The importance of protecting these systems during oil spills, both in the southeastern USA and elsewhere, cannot be overemphasized.

Brackish and salt marshes originate as tidal flats that are sites of relatively quiet water deposition at the high-tide line. As the flat is built up to or slightly above man sea level, marsh grasses take root. Once grasses grow on the flat, the sedimentation process is accelerated because of the baffling effect of the plants.

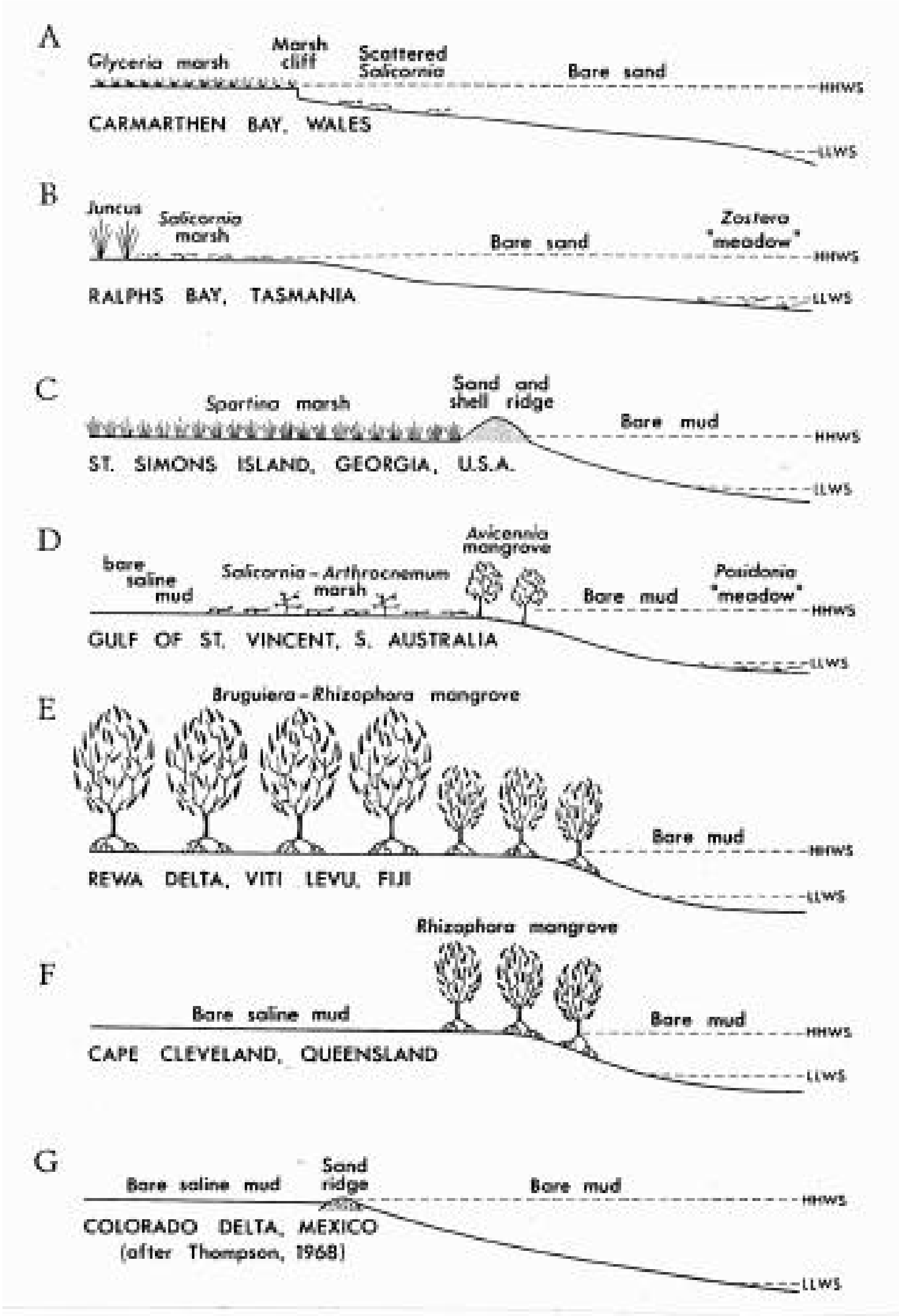


Figure 3-27. Relationship of coastal vegetation zones to geomorphic zones in a variety of climatic and physical settings. Profiles are diagrammatic and not to scale. (From Davies, 1973; Fig. 125.)

These marshes are, in effect, intertidal flats well-vegetated with halophytes (a plant that grows in salty soil; Basan and Frey, 1977). Marshes can prograde very rapidly, up to several cm/year, if the slope is flat and sediments are abundant.

For purposes of description, estuaries are usually subdivided into upper, middle, and lower zones. Freshwater marshes are most common in the upper estuary, where there are tides but very low salinities; brackish marshes occur in the middle estuary, where salinities generally average less than 15 parts per thousand (ppt); and salt marshes occur in the lower estuary, where salinities range from 15 ppt to the low 30s.

Lateral salinity changes up and down the estuary have a striking impact on the plant communities. Giant cordgrass (*Spartina cynosuroides*) is a conspicuous plant along the banks of the channels in both the upper and middle estuaries. Black needlerush (*Juncus roemerianus*) is by far the most common plant in the middle estuary, covering many thousands of acres in each estuary, and smooth cordgrass (*Spartina alterniflora*) dominates the lower estuary. See Figure 3-28 for a delineation of the distribution of the more conspicuous plants throughout estuaries of Georgia and South Carolina.

The lower reaches of the estuaries and landward margins of barrier islands of Georgia and South Carolina are bordered by salt marshes dominated by smooth cordgrass (*Spartina alterniflora*). The typical marsh profile found throughout the area is given in Figure 3-29. Most experts agree that plant distribution in the marshes is controlled by depth and duration of flooding (Barry, 1980); therefore, it is convenient to divide these marshes into a regularly flooded <u>low marsh</u>, the zone between mid-tide and neap high tide, and an irregularly flooded <u>high marsh</u>, which occurs roughly between neap and spring high tides.

Spartina alterniflora is the only plant that normally occurs in the low marsh zone, which is flooded 2-14 hours/day and has soil salt concentrations of 0.5-3.2 percent (Barry, 1980). The *Spartina* is usually quite tall (2-3 m at full growth) in the lower half of the profile (e.g., on creek banks and levees), but becomes dwarfed (10-50 cm) in the higher areas (e.g., between drainage creeks; behind levees). The reason for these differences in height is still a matter of conjecture.

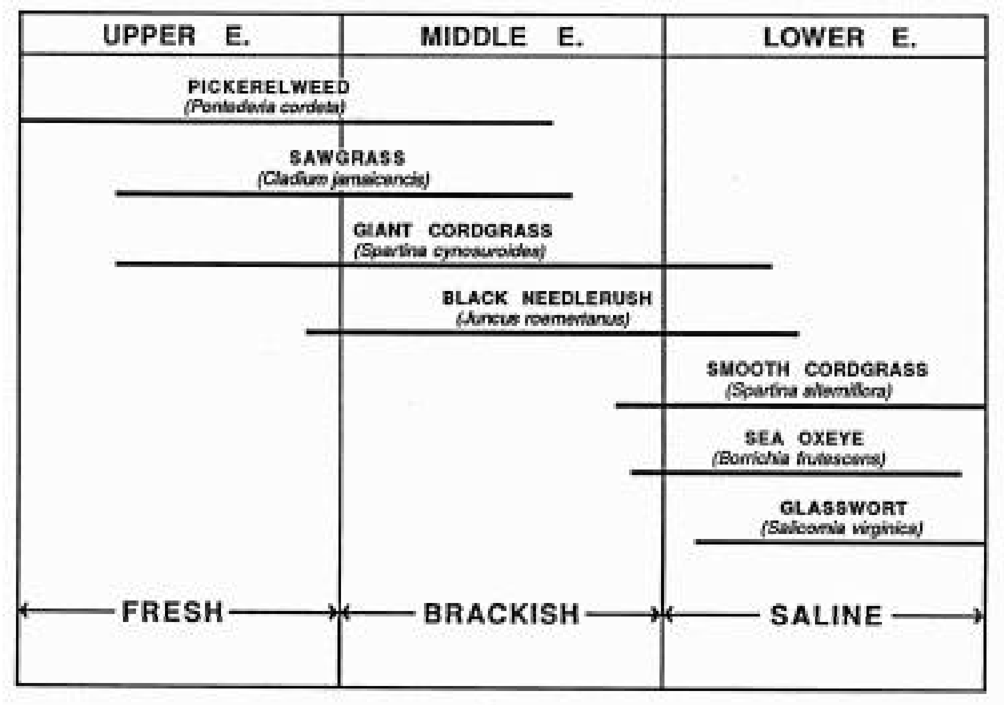


Figure 3-28. Occurrence of the most conspicuous plants in the marshes of the upper (fresh), middle (brackish), and lower (saline) parts of the estuaries of South Carolina and Georgia. (Modified after Stalter, 1974.)

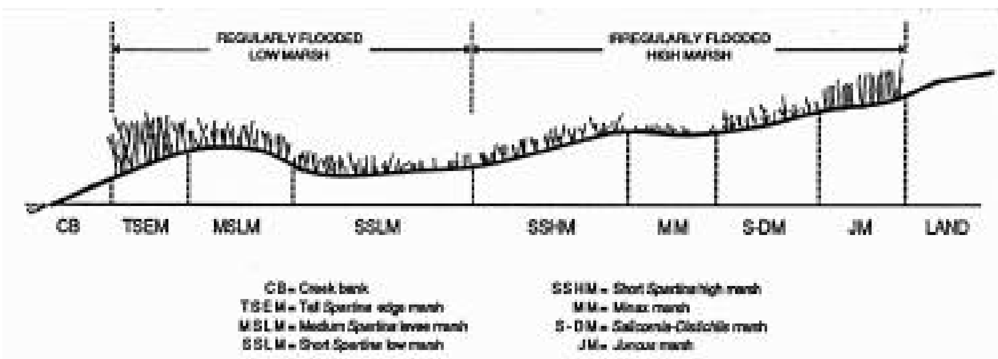


Figure 3-29. Typical profile of the salt marshes of South Carolina and Georgia. (Modified after Teal, 1958.) The “Minax marsh” zone is named after the dominant species of fiddler crab found there, *Uca minax*. The dominant plant is extremely short *Spartina alterniflora*.

At the lower elevations of the high marsh, zones of glasswort, or pickleweed (*Salicornia virginica*), sea oxeye (*Borichia frutescens*), and saltgrasses (*Distichlis spicata*) grow in soils with salt concentrations of 0.3-3.0 percent that are usually flooded daily. The upper high marsh, which is flooded mostly by spring tides, may be populated by *Juncus roemerianus*, in areas of lower salinity, and plants such as marshay cordgrass (*Spartina patens*), marsh elder (*Iva frutescens*), or sea myrtle (*Baccharis* sp.), in more saline areas.

Sediments in these marshes are typically muddy, and grain size decreases from the tidal channels to the highest portions of the marsh, except where runoff washes sand from adjacent sandy barrier islands or beach ridges onto the upper marsh (Edwards and Frey, 1977). Marsh sediments are always highly bioturbated, frequently being riddled with crab burrows (e.g., fiddler crabs; *Uca* sp.), having much the appearance of Swiss cheese.

The marsh sediments are commonly rich in organic matter, but they should not be referred to as "peat" unless the organic matter exceeds 70 percent of the sediment (by weight). Bona fide peat deposits rarely occur along tidal channels at the outer fringe of the marsh, where oil-spill impacts more often occur. Where peat does occur in estuarine marshes of the southeastern USA, it is usually found in the remotest, most freshwater portion of the marsh (e.g., in Snuggedy Swamp, South Carolina; Hayes and Sexton, 1989).

Marshes of California

In California, coastal wetlands are highly variable, depending upon the amount and frequency of freshwater influence. Southern California marshes are confined to narrow stream outlets with freshwater contribution only during the brief winter wet season (which can be completely missed during droughts). Thus, hypersaline conditions and salt-tolerant species dominate. Figure 3-30 shows a checklist of species within southern California salt marshes and Figure 3-31 shows the distribution of the most common halophytes by elevation. Soil salinity is the most important factor affecting salt marsh vegetation in Southern California (Zedler, 1982). Figure 3-32 shows a vegetation-succession model for Southern California marshes. The mature vegetation has *Spartina foliosa* restricted to the lower marsh, with the more salt-tolerant and opportunistic *Salicornia virginica* dominating the upper marsh.

HIGHER MARSH - LOWER MARSH

Juncus acutus	Frankenia palmeri	Lasthenia glabrata	Cressa truxillensis	Atriplex watsonii	Salicornia subterminalis	Cordylanthus maritimus	Limonium californicum	Monanthochloe littoralis	Frankenia grandifolia	Triglochin concinnum	Suaeda californica	Distichlis spicata	Cuscuta salina	Jaumea carnosa	Batis maritima	Salicornia bigelovii	Salicornia virginica	Spartina foliosa	
●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	Tijuana Estuary
●	●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	Sweetwater Marsh
					●		●	●	●	●	●	●	●	●	●	●	●	●	Mission Bay Marsh
●		●	●		●	●	●	●	●		●	●	●	●			●		Penasquitos Lagoon
●		●	●		●		●	●	●		●	●		●			●		San Dieguito Lagoon
			●		●				●			●		●			●		San Elijo Lagoon
●		●	●		●		●	●	●			●		●			●		Batiquitos Lagoon
●			●		●			●	●		●	●	●	●			●		Agua Hedionda Lagoon
●									●			●		●			●		San Luis Rey River Marsh
●		●	●	●	●		●		●		●	●	●	●			●		Santa Margarita River Marsh
					●				●			●		●			●		Las Flores Marsh
									●			●	●	●					San Mateo Marsh
●				●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	Upper Newport Bay Marsh
●				●	●		●	●	●		●	●		●	●	●	●	●	Bolsa Chica Marsh
●			●	●	●		●	●	●	●	●	●	●	●	●	●	●	●	Anaheim Bay Marsh
			●		●				●		●	●		●			●		Ballona Wetland
																			Malibu Creek
●		●		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	Mugu Lagoon
●									●			●		●			●		McGrath Lake
●									●			●					●		Santa Clara River
		●	●	●	●	●	●	●	●	●	●	●	●	●			●		Carpinteria Marsh
		●	●	●	●		●	●	●	●	●	●	●	●			●		Goleta Slough
			●						●			●	●	●			●		Deveraux Lagoon

Figure 3-30. Check list of species within salt marshes of southern California wetlands. Data are cumulative lists from a variety of sources, including observations of W. Ferrens (UCSB Herbarium) and J. Zedler. Wetlands with a history of good tidal flushing are boxed on the right-hand column. (From Zedler, 1982.)

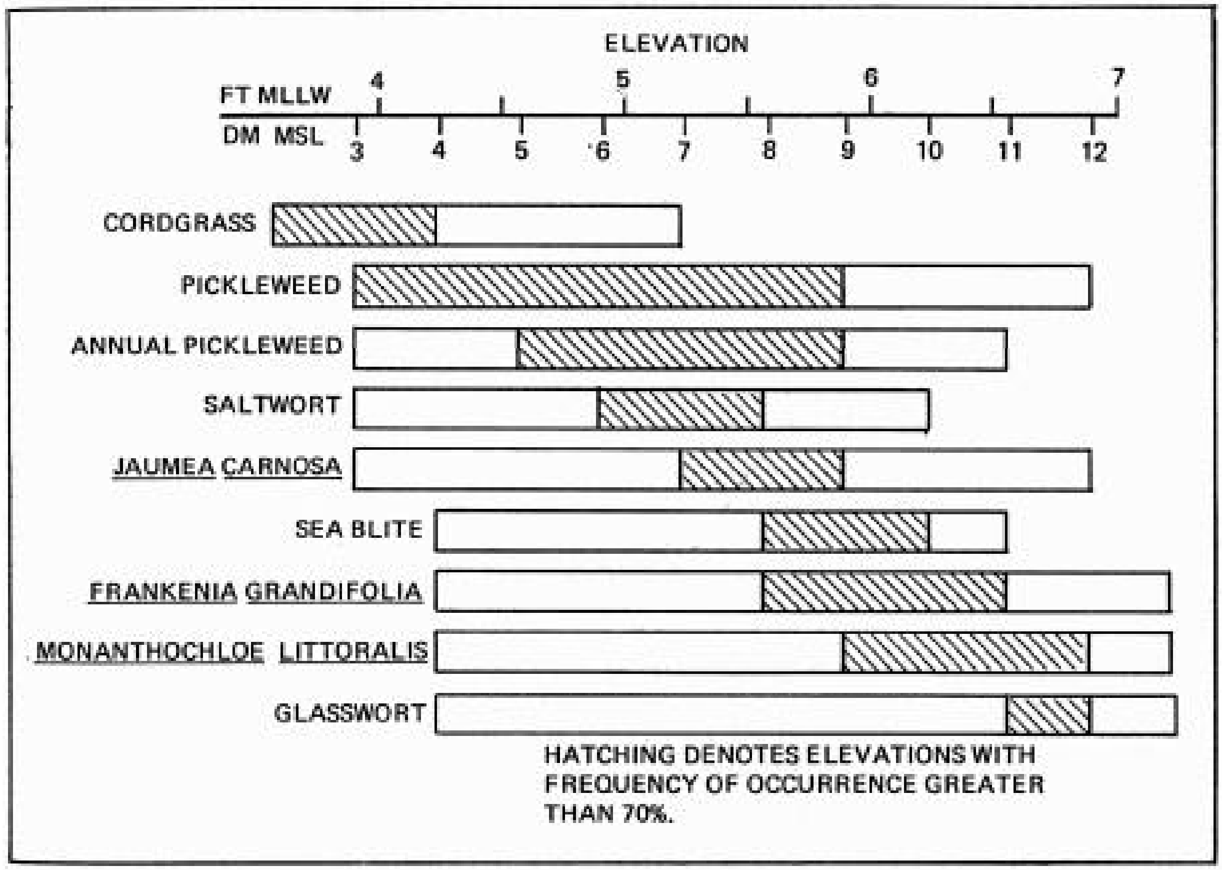


Figure 3-31. Distribution of the most common halophytes by elevation, at Tijuana Estuary. Data from Anaheim Bay were used to extend the ranges of species beyond the 3- to 12-dm MSL range observed at Tijuana Estuary. (From Zedler, 1982.)

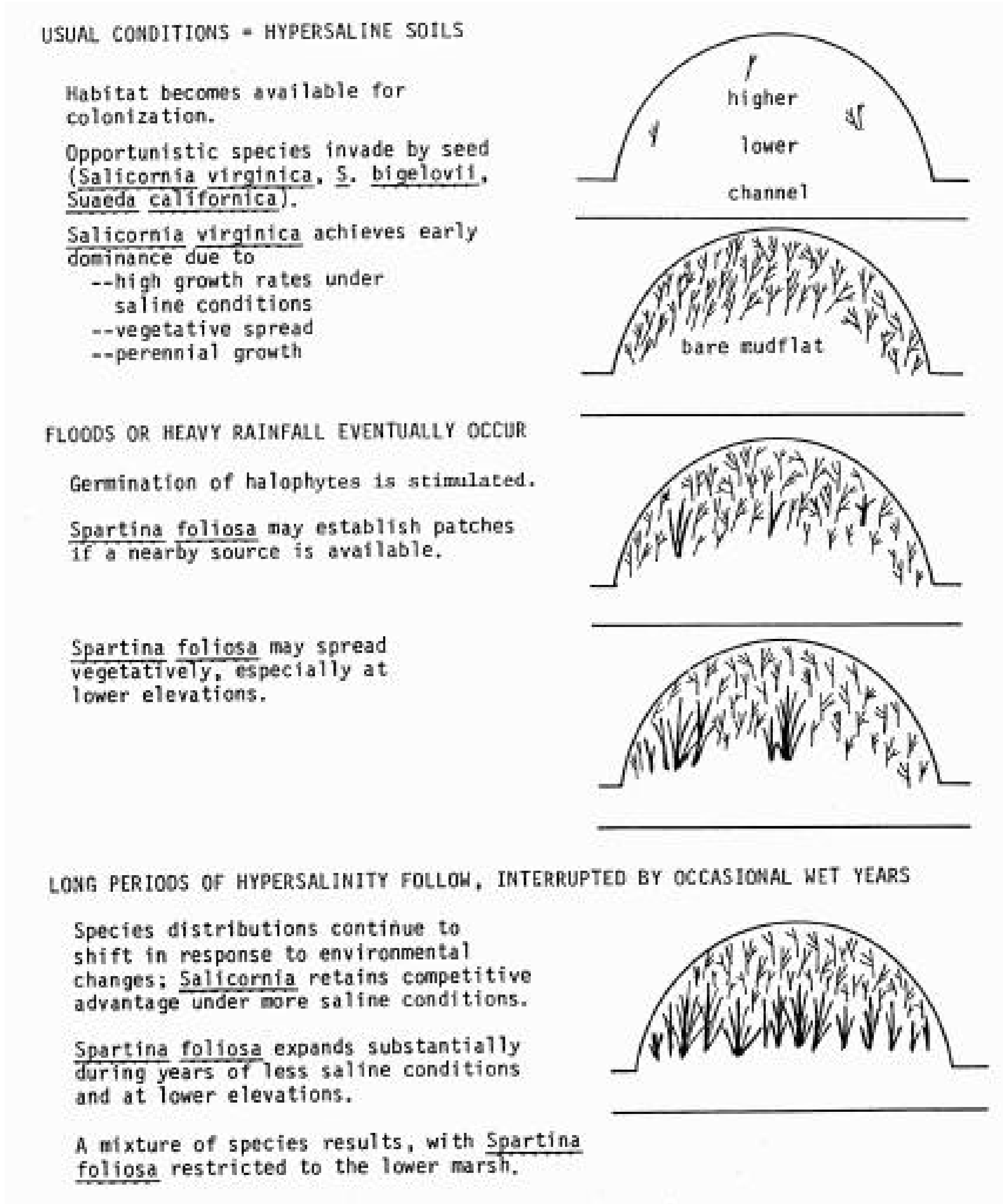


Figure 3-32. Conceptual model of species establishment and spread in southern California salt marshes. (From Zedler, 1982.)

San Francisco Bay and the Sacramento-San Joaquin River Delta have a diverse and variable salt marsh community, with about 125 species of vascular plants reported in the area. The following summary of the distribution of species is from Atwater et al. (1979).

Common pickleweed (*Salicornia pacifica*) and California cordgrass dominate the tidal-marsh vegetation of the Bay, with common pickleweed monopolizing the vegetation at elevations near and about MHHW. Other common plants include salt grass (*Distichlis spicata*), marsh Grindelia (*Grindelia humilis*), halberd-leaved saltbush (*Atriplex patula*), alkali heath (*Frankenia grandifolia*), and fleshy Jaumea (*Jaumea carnosa*). California cordgrass fringes tidal-marsh plains where they descend into mudflats; near MTL it forms pure stands. Common tule (*Scirpus acutus*), Olney's bulrush (*Scirpus olneyi*), common reed (*Phragmites communis*), and cat-tails (*Typha* sp.) dominate islands of pristine marsh in the Delta. The tidal marshes of San Pablo Bay, Carquinez Strait, and Suisun Bay represent complex transition communities, which are even more complex because of long-term changes in salinity from water diversions and multi-year droughts. There can be gradual changes in soil salinities during droughts which favor or discourage certain species.

Behavior of Oil in Marshes

Most of our experience comes from the study of spills affecting vegetation under tidal influence in coastal estuaries. And most of the studies have been of marshes dominated by *Spartina*, sp. Based on the available data, there are significant differences among species assemblages.

When oil comes in contact with a marsh in a tidal setting, it generally behaves in the following manner:

- Oil adheres readily to the vegetation; in fact, marsh vegetation is a very effective oil sorbent.
- The band of coating will vary widely, depending upon the tidal stage at the time that the oil slicks are in the vegetation. There can be multiple bands.
- Large slicks will persist through multiple tidal cycles and coat the entire stem from the high-tide line to the base.

- Fresh crudes and heavy oils will tend to “slide” down the stem over time in warmer weather and pool on the sediments at the base of the plant.
- Weathered oils do not “slide” as much; the oil stays on the vegetation.
- If the vegetation is thick, heavy oil contamination can be restricted to the outer fringe, with penetration and lighter oiling up to a 10 m width.
- Lighter oils (light refined, fresh crudes) can penetrate deeply, to the limit of tidal influence.
- Medium to heavy oils do not readily adhere to or penetrate the wet, muddy sediments, but they can pool on the surface and in burrows.
- Light oils can penetrate the top few cm of sediment and deeply into burrows and cracks (up to 100 cm).

Factors Affecting the Impacts of Oil on Marshes

Although every spill is a unique combination of events, there are several factors which affect the behavior and impact of the oil on the marsh ecosystem:

1) Oil type
2) Extent of contamination of the vegetation
3) Degree of contamination of the sediments
4) Exposure to currents and waves which effects the speed of natural removal
5) Time of year of the spill
6) Species sensitivity
7) Damages associated with cleanup activities

Impacts by Oil Type

It has been shown that light refined products have the greatest acute toxicity to marsh vegetation, when compared to other types of oil.

Spill/Experiment	**Observations**
Florida barge, No. 2 fuel oil (Burns and Teal, 1979)	*Spartina* killed; no regrowth after 16 mo. where sediments had > 2,000 ppm fuel oil

Bouchard No. 65 barge, No. 2 fuel oil, Buzzards Bay, MA (Hampson and Moul, 1978)	Total mortality of *Spartina* and *Salicornia*; no reseeding or rhizome growth in 3 yrs in zone heavily oiled; 2-4x slower growth elsewhere. Erosion rates were 24x greater in oiled areas.
Four oil types tested on *Spartina* (Alexander and Webb, 1983)	All oils caused mortality within 3 weeks; after 5 mo., only plots with No. 2 fuel oil had reduced growth of plants, compared with 2 crudes and No. 6 fuel oil.

In contrast, observations of spills of crude oils and heavy refined products show mostly short-term impacts, and recovery within 1-3 years (Baker, 1971; Baca et al., 1985; 1977; Bender et al., 1980; Michel, 1989). There are even studies which show that an increase in standing crop of the marsh grass occurs following some spills (Hershner and Moore, 1977). Crude oils contain nitrogen, and when nitrogen is limiting, there can be growth simulation under some conditions (Leendertse and Scholten, 1987). However, the net impact is always negative.

Extent of Vegetation Contamination

The extent of vegetation contamination is another very important factor. Many plants can survive partial oiling; few survive when all or most of the stem is coated. Examples from the literature are:

Spill/Experiment	**Observations**
Cape Fear River, NC, No 6 fuel oil (Baca et al., 1983)	After 5 mos., lightly oiled *Spartina* had recovered; heavily oiled areas showed reduced no. of plants/m^2 and sediment oiling.
Four oil types tested on *Spartina* (Alexander and Webb, 1983)	Highest mortality was observed in plots where oil was applied to entire plant surface, compared to on the sediment and lower plant
Field oiling with crude oil on *Spartina* stems, not leaves (DeLaune et al., 1979)	No initial mortality or difference in above-ground biomass or stem density for 2 growing periods.

Degree of Sediment Contamination

The degree of contamination of sediments is another very important factor, which can prolong impacts to marsh ecosystems for many years, compared with the initial loss of oiled vegetation. Slower recolonization rates are frequently related to hydrocarbon levels in the sediments, though it should be noted that the composition of the oil is as important as the total petroleum content. That is, fresher oil and refined products have higher percentages of the more toxic fractions in oil, whereas heavy oils have lower initial and long-term toxicities. Examples are:

- 5,000-50,000 ppm of a light crude slowed growth of *Spartina* for 18 months in field oiling experiments. Growth was unaffected at lower concentrations (Alexander and Webb, 1987).
- No regrowth of *Spartina* in sediment with >2,000 ppm No. 2 fuel oil following the *Florida* spill (Burns and Teal, 1979).
- In 2-year studies of restoration through sediment stripping following a No. 6 fuel oil spill in the Potomac River, Krebs and Tanner (1981) found:
  -Little impacts to vegetation at concentrations <2,000 ppm
  -Rhizome death and no regrowth at concentrations >10,000 ppm.

Exposure

The physical setting of the oiled marsh, relative to exposure to waves and currents, is one of the most important factors controlling the persistence of oiled vegetation and overall rate of recovery. Exposure can work to speed recovery, but, in some cases, it can also work to increase erosion after plant roots die and before new growth can occur.

Oil deposited along the outer fringe is removed as the vegetation dies back and is exported. There are many examples of oiled vegetation along tidal rivers where, after one season, there is no visual evidence of oiled vegetation or sediments. Boat wakes, river currents, and tidal flushing are important natural removal processes, and they are usually much more effective than any man-made cleanup. In contrast, oil spilled in interior settings, such as from pipelines crossing wide marsh or swamp areas, have no physical removal mechanisms, and the oil can only weather in place or be removed by cleanup efforts.

Seasonal Effects

The timing of an oil spill, relative to the plant’s growing season, can affect the nature and duration of the spill impact. In general, oiling during the dormant winter season has the lowest impact, whereas oiling of vegetation during the summer growing season had longer effects. The mechanisms responsible for the slower recoveries from a spill during the growing season have not been adequately studied, but probably are related to plant stress at a time when the plant's resources are being fully expended. For example, oiled plants rarely flower and oiled flowers do not produce seed (Baker, 1979), resulting in loss of the year's seed production. Alexander and Webb (1985) found that, in experimental plots, the time of year the oil was applied did not influence the response of *Spartina* to oil when it was applied to sediments and the lower portions of the plants; however, when the entire plant surface was oiled, impacts were greater for a May versus a November oiling.

If oil persists, then there can be delayed impacts to marshes. Thomas (1977) reported delayed toxicity of heavy surface oiling by No 6 fuel oil to *Spartina* the second year after the *Arrow* spill in Chedabucto Bay.

Species Sensitivities

There are some known variations in sensitivity among species, however, very little else is known about other species. In general:

- Annuals are less resistant than perennials, which have large roots systems that allow them to regrow after damage to aerial portions (Getter et al., 1984); for example, the annual *Salicornia* is less resistant than other species, such as *Spartina*, to oil spills (Baker, 1971)
- *Juncus* is more resistant than *Spartina* to chronic spills (Lytle and Lytle, 1987)

Impact of cleanup

Sometimes, the greatest impact of an oil spill on a marsh is a result of the cleanup efforts. The greatest damages derive from:

- Destruction of the root system by trampling
- Mixing oil deeper into the sediments, slowing weathering and removal
- Removal of surface sediments suitable for supporting new growth
- Smothering of vegetation by mobilized sediments
- Exposure of the interior of the plant to toxic substances in the oil

Nowadays, responders are very sensitive to causing more harm during cleanup than what will result from the oil alone. Most of the time, very little cleanup is conducted in marshes, other than passive collection of oil onto sorbents. However, there are two conditions where cleanup can be warranted: 1) when heavy oil has pooled in a marsh sheltered from natural removal processes, and 2) when other uses or resources present are at risk from leaving the oil in place. The biggest controversy is over cutting of the oiled vegetation. Again, most all of the experience is vegetation cutting is of *Spartina* along the east and Gulf coasts. The literature is summarized below.

Spill/Experiment	**Observations**
Cape Fear River, NC, No 6 fuel oil (Baca et al., 1985)	After 15 mos., uncut *Spartina, Scirpus, and Phragmites* showed good recovery; cut *Spartina* showed no recovery.
Four oil types tested on *Spartina* (Alexander and Webb, 1983)	Clipped plots showed regeneration by growth of new stems and seedlings, but No. 2 fuel oil and Light Arabian crude inhibited stem emergence.
Crude oil spill, TX into sheltered *Spartina* marsh (Holt at al., 1978)	6 mos. later, only heavily oiled vegetation showed impacts; clipped areas showed slightly better recovery than non-cleaned, except where physical damage to roots occurred.
Nepco 140 barge, No. 6 fuel oil in St. Lawrence River (Alexander et al., 1981)	Cattails were cut below water level in June 1976. Next spring growth was normal but no flowering occurred.
Light Arabian crude in Neches River, TX in January 1979 (McCauley and Harrel, 1981)	Cut *S. patens* showed no or minimal growth, whereas leave-alone plots showed normal growth through next growing season.
Louisiana crude applied to sediment surface of plots (DeLaune at al., 1984)	Cutting of vegetation reduced plant growth and slowed rate of recovery, compared with oiled only and unoiled plots.

Mangroves and Coral Reef Communities

The dominant estuarine and nearshore coastal communities in tropical and some subtropical regions are mangroves and corals. These environments are very important to the ecological balance of many of the marine ecosystems in the tropics. Like the salt marshes of the temperate zones, mangroves and coral serve as nursery habitats and have a high diversity and density of animal and plant species. Mangrove photosynthetic activity provides the base for secondary productivity, in the form of leaf detritus, that supports important commercial and recreational fisheries. They provide habitat for endemic and endangered species.

The impacts to these environments from spilled oil is dependent on the amount and type of oil spilled, extent of weathering of the oil prior to landfall, and the physical characteristics of the impacted area (water depth, exposure to waves, nearshore and intertidal topography, sediments, etc.). Each of these factors will be discussed as they determine the sensitivity of coral and mangrove ecosystems to oil spills.

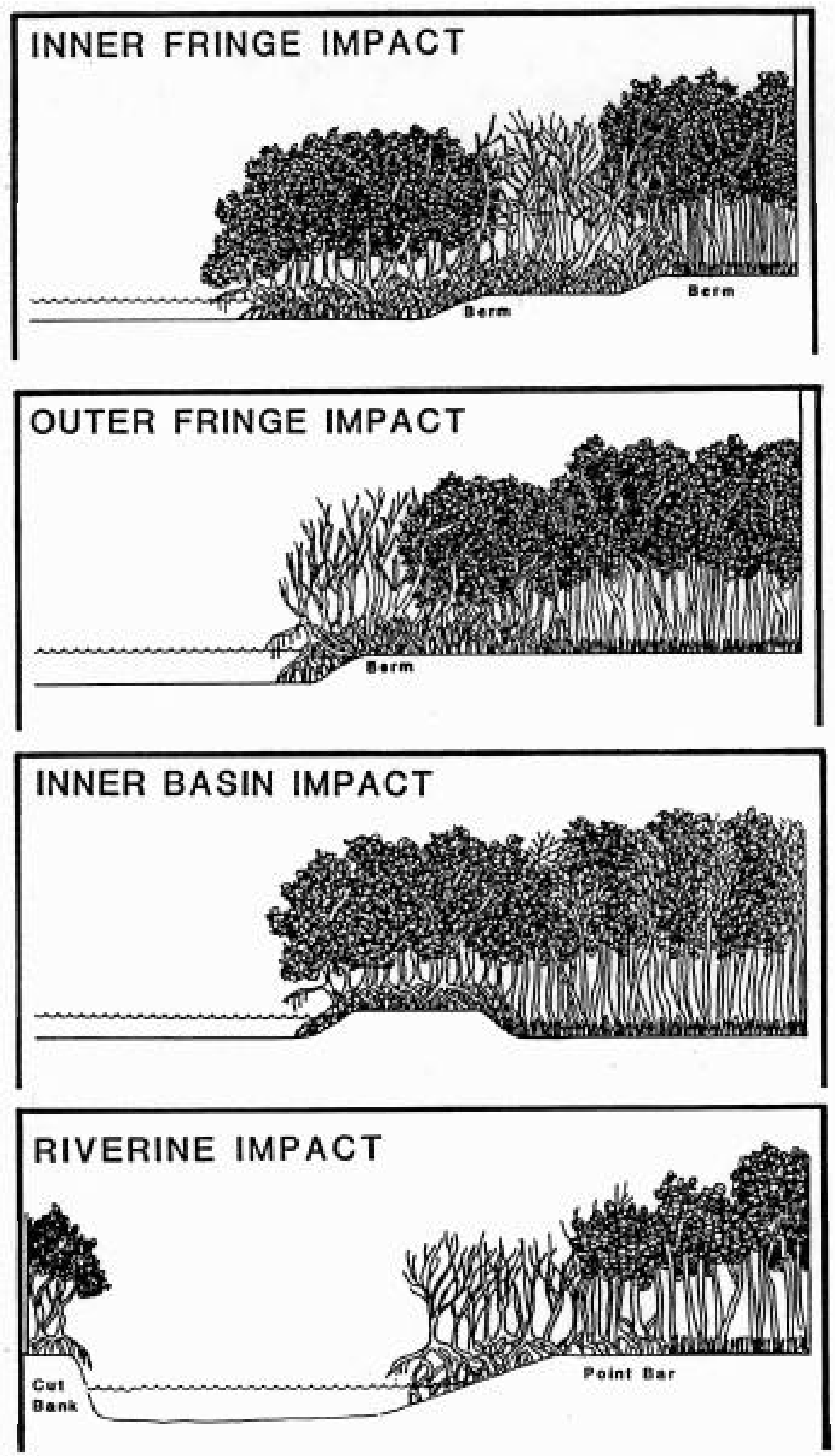
Mangroves

The two most common species of mangroves found in the United States are the red mangrove (*Rhizophora mangle*) and the black mangrove (*Avicennia germinans*). The red mangroves have gracefully curving prop roots which extend a meter or more above ground and are covered with small pores, called lenticels, through which oxygen diffuses when exposed to the air at low tide. Because mangroves grow in anaerobic soils, they obtain most of the oxygen needed from the atmosphere. Black mangroves uptake oxygen through small roots, called pnematophores, which extend 20-30 centimeters straight up above the soil from an underground root system. Where both species exist, red mangroves occur in the low- to mid-intertidal zones, whereas black mangroves are more common in the upper intertidal and supratidal zones. Black mangroves are less tolerant of high salinities, so they grow better where there is less exposure to salt water inundation and some fresh groundwater influence. The white or buttonwood mangrove (*Laguncularia racemosa*) occurs primarily seaward of the black mangrove.

Where mangrove forests occur, water depths are very shallow and most of the forest is exposed during low tide on a regular basis. They are frequently fronted by shallow seagrass or reef flats. Topographic elevations in the forest control the location and extent of oiling from floating slicks. Figure 3-33 depicts four types of physical impacts likely to occur during oil spills (Getter et al., 1981).

Inner fringe impacts occur when there is a berm behind mangroves growing in the subtidal or low intertidal areas. The oil passes through the open network of prop roots and collects at the front of the berm, causing defoliation and mortality of both seedling and adult trees at the inner stand of mangroves. The prop roots of the outer mangroves are oiled, but only as a thin band. Greatest impacts occur where the oil is concentrated in the sediments and wrack is piled on top of the berm. This

Figure 3-33. Four models of the distribution of oil spill effects in mangroves.



interior berm is either inherited topography or built by the accumulation of sediment and debris carried into the forest by storm waves. The berm serves to prevent the transport of oil deeper into the forest, so where present, the berms are the *de facto* interior limit of oil penetration. The natural rate of flushing of oil from these inner berms is highly variable. Large amounts of debris may be indicative of accumulation zones with slow removal rates. Heavy debris also acts as a natural sorbent for oil, with the potential as a long-term leaching source.

<u>Outer fringe impacts</u> are likely along relatively steep intertidal zones where red mangroves commonly occur in a narrow band. Because of the narrow intertidal zone, there can be heavy oiling of the sediments and any accumulated debris. The steepness of the intertidal zone may be due to a wave-built sand beach or a steep rocky shore. The presence of a sand beach indicates exposure to waves and the potential for removal of stranded oil by natural processes. A rocky substrate may indicate wave exposure, but is not as diagnostic as a depositional beach. There may be very sheltered bays where mangroves have been established on a rocky substrate. However, oil is less likely to contaminate and persist in the rocky substrate than in fine-grained sediments.

<u>Inner basin impacts</u> occur where there is a low overwash berm in front of a shallow depression or interior basin. Oil gets washed over the low berm and is trapped in the basin. Although the oil can spread over a large area, the oil is less likely to be concentrated in a narrow band, thus partial defoliation as shown on Figure 3-33 often occurs. Persistence of the oil can be long term, depending on the degree of natural flushing in the basin. In more exposed areas, oil can be removed from the system within several months, particularly for refined products and light crudes. Heavy oils are always more persistent because of their higher viscosities. In sheltered areas, oil persistence of years is likely.

<u>Riverine impact</u> is very similar to outer fringe impact, however, it occurs only on river point bars, and it can be more extensive than outer fringe impacts. Of course, if the spill occurs during unusually high water levels, the oil can be carried over the bars and river levees, into the interior basin forests. Riverine environments are, however, relatively high energy, being exposed to both riverine and tidal currents which are effective in natural removal of the oil.

The type of oil greatly affects the nature and degree of impacts to mangrove ecosystems. Refined petroleum hydrocarbons with large amounts of the water-soluble aromatic compounds (e.g., jet fuels, gasoline) are more acutely toxic to mangroves at lower concentrations than are crude oils and heavy refined products.

The best example of the high acute toxicity of light refined products is the 1986 spill of 60,000 gallons of JP-5 from the Roosevelt Roads Naval Station in Puerto Rico (RPI, 1987). The oil had a low viscosity so there was no smothering and the only impacts were due to direct exposure and poisoning via absorption through the pneumatophores and prop roots. An estimated 70 percent of the oil evaporated within 24 hours, however, a thin slick was blown across a small bay and was quickly deposited in a tidal mixed species assemblage of red, black, and white mangroves, with reds dominating the seaward zone and blacks dominating the landward zone. Trees exhibited stress in 10 days, and within 5 months, 5.5 hectares of trees were dead. This acreage of mortality is disproportionately large for the number of gallons spilled, compared to heavier oils.

It was interesting to note that seedlings survived more than adult trees because the seedling roots were buried in sediments and avoided acute exposure. Seedling mortality for the period 6-9 months post-spill averaged 30 percent, which not different from non-oiled sites. Chemical analysis showed no residual oil in the sediments, so natural recovery was predicted to occur unimpeded by contaminated sediments. Natural recovery depends on adequate supply of seeds and growing conditions, including regular flushing by clean seawater, which provides stabilized surface and interstitial water salinities, brings in nutrients, and increases colonization rates by transport of seeds into the area. Following this incident, a restoration plan was developed to open selected channels to increase the level of circulation in parts of the forest which had low flushing rates.

Heavier oils (Bunker C and medium to heavy crudes) lead to chronic exposure and chronic impacts to the mangrove ecosystem. Oil impacts to the trees are related to the physical coating of the roots, which prevent gas exchange, and from chronic exposure to oil-contaminated sediments. Such exposure can result in slow defoliation and death over a period of time. If mortality does not occur, signs of severe stress will be manifested, such as partial defoliation, low survival of propagules, leaf deformities, reduced leaf size, and increased insect infestation (Lewis, 1983).

Seedling and propagules die when they are coated with oil, even when the oil has weathered for a few days before stranding. It should be noted that where defoliation and death of adult trees occurs following a spill, seedling density increases significantly. Because of the newly opened canopy, more light reaches the seedlings and they have higher sprouting rates. However, where the sediments remain contaminated, long-term seedling survival is lower. Even eight years after the *Zoe Colocotronis* oil spill in Puerto Rico, seedlings in heavily oiled sediment appeared chlorotic, stunted, and insect damaged (Cintron et al., 1981). After the 1986 Texaco spill of 50,000 barrels of a medium-light crude oil in Panama, sediments were toxic to planted seedlings for the first six months post-spill, but after twelve months survival was the same for control and oiled sites (Teas et al., 1989).

Impacts to the associated fauna and flora can be severe. Red mangrove prop roots support a dense community of attached algae, mussels, oysters, and barnacles, which are frequently directly killed under moderate to heavy oil coating. Crabs are particularly hard hit, whereas gastropods appear to be able to shift to less contaminated areas, if present (Getter et al., 1980; Jernalov et al., 1976).

Laboratory studies have shown wide variability in the relative toxicity of different types of oil in sediments on seedling survival. Table 3-2 summarizes the results of experiments by Getter et al. (1984). No. 2 fuel oil was shown to be the most toxic, compared to Bunker C and two crude oils. Bunker C was the least toxic oil tested. Black mangroves exhibited higher mortalities and sublethal stress effects than red mangroves at the same dosages and were found to be especially sensitive to aromatic compounds. Similar results were reported from studies conducted at the Universiti Sains Malaysia (Lai and Feng, 1984).

Extensive laboratory and field studies were conducted in the 1980s to determine the relative toxicity of oil versus dispersed oil. In fact, the previously mentioned laboratory studies were the oil-only controls for comparison with dispersed-oil treatments. These studies have been conducted by RPI (Getter et al., 1984; Ballou et al., 1985) and researchers at Universiti Sains Malaysia (Lai and Feng, 1984). The results of these studies include:

Table 3-2. Concentrations of different types of petroleum hydrocarbons and observed toxic effects from laboratory experiments (Getter et al., 1984).

CONCENTRATION	FUEL TYPE (in ppm)	TOXIC EFFECTS
100	Diesel	Growth alteration
300	No. 2	92% mortality; survivors with no new leaves
300	Bunker C	24% mortality; survivors with fewer new leaves
300	South Louisiana crude	20% mortality; survivors with fewer new leaves
300	Kuwait crude	No mortalities; increased number of new leaves
1,000	Diesel	Growth deformities
10,000	Diesel	Lethal
38,600	Bunker C No. 2 Kuwait crude	Fewer new leaves; depressed weight gain
100,000	Diesel	Lethal

- Dispersed Bunker C was less toxic than undispersed Bunker C.
- Dispersed light Arabian crude and No. 2 fuel oil resulted in increased defoliation.
- Toxicity can result from oil entering roots and being drawn up the stems and leaves by transpiration.
- In field experiments, dispersed oil had minor effects on mangroves whereas untreated oil caused extensive defoliation and death to adult trees, lower survival rates of planted propagules, and long-term sediment contamination.
- Black mangroves are more sensitive to oils, both dispersed and untreated.

Based on both laboratory and field studies of oil spills in mangroves, the following comments and recommendations are made:

Light Oils (Gasoline, Jet Fuel, No. 2 Fuel Oil)

- Fresh spills will have acute, toxic impacts to both trees and intertidal biota.
- Sunny, windy weather will speed evaporation which will lessen water-column and intertidal impacts.
- These light products will penetrate deeply into the forests, stopping only at the high-tide line. Highest concentrations will occur at the high-tide line and in detrital material.
- Persistence of oil in sediments should not be great, unless there has been physical mixing into the substrate by wave or cleanup efforts.
- No. 2 fuel oil will have the greatest persistence; it can persist and remain toxic for many years if it penetrates burrows and prop root cavities.
- It is generally impossible to physically protect a fringing mangrove forest.
- Deployment of booms is seldom effective because of low viscosity of these light products and importance of water-column transport mechanisms, but it should be attempted, particularly at stream mouth.

Crude Oil/Heavy Refined Products

- Oil will coat intertidal zone, with heaviest concentrations either at the outer fringe or the high-tide line.
- Penetration into the forest will be limited by the amount of oil, forest density, and oil viscosity; weathered, emulsified oils penetrate less.
- Oil can pool onto sediment surfaces and accumulate heavily in detrital material such as seagrass wrack.
- Toxicity is due to coating and sediment contamination; there is little difference in toxicity among the heavier crude oils and refined products.
- Because of low physical energy in mangrove swamps, oil persistence is great and sheens are generated for months.
- Boombs should be deployed to attempt to protect the most sheltered areas where greatest persistence is likely.

Cleanup Recommendations

- Under light accumulations of any type of oil, no cleanup is recommended.
- If sheens are present, use sorbent booms to pick up the oil as it is naturally removed, being sure to change booms frequently.
- The only light refined product that might require cleanup is No. 2 fuel oil/diesel because of the potential for sediment contamination.
- Heavy accumulations could be skimmed or flushed with low-pressure water flooding, as long as there is NO disturbance or mixing of oil into the substrate. If substrate mixing is likely or unavoidable, it is better to leave the oil to weather naturally.
- Under moderate to heavy accumulations of crude or heavy refined products, a detailed, site-specific cleanup plan will be required. This cleanup plan should be prepared by experienced personnel and include:

    1. General map of entire area impacted and locations of specific areas to be cleaned.
    2. Detailed maps of each specific area showing the oil locations and type of cleanup to be performed at each location.
    3. Definition of each type of cleanup.
    4. Specific restrictions to prevent further damage.

- Oily debris should be removed, taking care not to disturb the substrate.
- The vegetation should never be cut or otherwise removed.
- Sorbents can be used to wipe heavy oil coating from prop roots in areas of firm substrate and with close supervision.

Coral Reefs

Coral reefs are mostly subtidal in nature, although the most shallow portions of some reefs can be exposed during very low tides. The three major categories of reefs are:

- Fringing reefs - long, narrow bands of coral reefs parallel to and near the shoreline. When near coastal development, they are susceptible to stress from sedimentation and chronic pollution.

- Barrier reefs - similar to fringing reefs except thay are further offshore and much broader (e.g., the Great Barrier Reef of Australia).

- Atoll reefs - reefs formed by buildup of coral on the rim of a subsiding volcano. They are circular or portions of a circle, forming a sheltered lagoon.

All of the reefs are completely submerged during high tide, and only a few reefs are routinely exposed during normal low tides. More commonly, reefs are exposed only during extreme low tides a few times a year.

Review of the literature shows that there have been relatively few studies of reefs following exposure to oil spills. There are several very good summaries of the literature as of the early 1980s. Loya and Rinkevich (1980) and Ray (1980) compiled data on known oil spills near coral reefs and their effects on coral reef communities. Tetra Tech (1982) prepared a draft report for the American Petroleum Institute on ecological impacts of oil spill cleanup on nine different habitats, including coral reefs. They updated the Loya and Rinkevich (1980) list of oil spill case histories, for a total of fifteen. These case histories have very little quantitative data, but they mostly indicate no or very short-term impacts to coral reefs, except where chronic spills occured. It is important to note that these case histories looked for acute impacts, whereas it is more likely that any negative effects will be manifested as sublethal responses (Fucik et al.,1984).

There have been very few additional studies of coral reef impacts by oil spills reported in the literature since the mid-1980s. There have been laboratory studies, comparing oil versus dispersed oil impacts (Dodge et al., 1984; Knap et al., 1985; Wyers et al., 1986; Knap, 1987), and studies on the effects of chronic oil pollution (Bak, 1987). The only exception is the extensive followup to the 1986 Texaco spill in Panama which impacted shallow coral reefs near the Galeta Marine Laboratory of the Smithsonian Tropical Research Institute. Guzmán et al. (1991) reported on the short-term impacts of the spill after 2.5 years, with delayed and extensive patterns of injury observed. This spill had three factors which contributed to the extent and degree of damage to coral reefs: 1) large amounts of fresh oil, 2) shallow-water reefs, and 3) chronic exposure for months as the oil leached out of adjacent mangroves.

The potential for impacts from oil spills on reefs can be divided into three main categories, as summarized below:

Low risk

- Reefs located at greater than five meters water depth at low tide; dilution should reduce oil concentrations in the water column to below acute toxicity levels.

- High energy setting could mix fresh oil into the water column, but exposure is more likely to be short (hours to one day).

- Studies have shown healthy reefs rapidly recover from sublethal effects [i.e., normal carbon fixation restored within 5-24 hours after exposure (Knap, 1987)].

- Where the reef is exposed to heavy surf, deposition of oil is unlikely.

Medium risk

- Reefs located in water depths of 1-5 meters below low water, where high concentrations of dissolved and particulate oil are possible, especially when the oil slick is fresh.

- When the oil is fresh, toxic concentrations may cause acute impacts; more likely sublethal impacts may occur (NAS, 1985):

  -Increased algal growth

  -Slower growth rates

  -Lower fecundity (lower number of ovaria per polyp, fewer larvae per coral head, and lower settlement rate of planulae)

  -Localized tissue rupture

  -Premature expulsion of larvae

  -Excessive mucous production

- Degree of impact from a spill will be determined by:

  -The oil type

  -How much oil is likely to be mixed into the water column

  -How much weathering of the oil has occurred

High risk

- Intertidal reefs and reef flats, where direct contact with the oil is likely.
- Sheltered, shallow water settings, where high concentrations of oil are likely to persist.
- Where leaching from adjacent area creates a chronic source of oil exposure.
- Where coral reef communities are already stressed by pollution, sedimentation, thermal quality problems, etc.

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4 Biological Resources

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Chapter 4.
Biological Resources

Introduction

Determining which biological resources may be at risk in an environment threatened by an oil spill is an important part of spill response. This information will be an integral part of establishing priorities for protection efforts, and deciding on an appropriate response strategy. The following questions about biological resources are some of the first that will need to be answered during a spill event:

- What are the biological resources (including birds, plants, invertebrates, fish, mammals) that inhabit the areas potentially impacted? (Consider as well, human uses of resources, such as fisheries and recreational activities)

- What is the likelihood that these resources will be impacted by oil, and what kind of impacts can be anticipated?

- How sensitive are these resources to oil?

Answers to these questions will provide the information needed to address related issues, including establishing priorities for habitat protection, and evaluating possible response strategies.

Evaluating resources at risk

When drawing up a list of the resources at risk in a given area, seasonal migrants as well as resident populations should be included. Detailed information on the life stages present at any given season will aid in determining the sensitivity of different populations.

For advance planning, regions may wish to establish databases on biological resources and habitat locations in their region. Resource information should be updated periodically. Other available sources of information include state resource agencies, Federal agencies (such as U. S. Fish and Wildlife Service for information on birds and some mammals, NOAA for fisheries and marine mammals), experts from local academic or other institutions, Environmental Sensitivity Maps (ESI) and personal knowledge.

Factors affecting oil impacts on biota

A number of different factors will determine the degree of effects that can be expected from an oil spill. These can be grouped into degrees of severity, such as, heavy, long-lasting effects, intermediate levels of effects, and comparatively little or no effects (NAS 1985). The following factors, many of which have been discussed previously, will all be important in determining the levels of impact on biota:

- *Geographic location*

- *Oil dosage and impact area*
  Different habitat types within an area may be impacted quite differently. For example, in the intertidal zone, the lower intertidal usually contains the most diverse group of species. Frequently, however, oil impacts are heaviest in the upper intertidal zone. This was the case in many parts of Prince William Sound after the *Exxon Valdez* spill.

- *Oceanographic and meteorological conditions*
  The physical exposure and weather conditions at a site will determine not only where oil may strand on the shoreline, but will also indicate how quickly oil will weather once stranded on that shoreline. Habitats in high energy environments will likely experience much shorter residence time of oil than habitats in sheltered, low-energy environments.

- *Season*
  Population concentrations of species that may be present in the impacted area will include those that are not year round residents, but may be present seasonally in large aggregations. These will include migratory birds, and mammals, and fish spawning aggregations. Season and temperature will also determine the behavior of species present in the area that may affect their vulnerability to oil. An example is salt marsh crabs which were impacted during winter by a spill in Arthur Kill, New Jersey. Oil in sediment drove the crabs out of their burrows during extremely cold temperatures, causing increased mortality (Burger et al. 1991).

- *Oil type*
  The toxic properties of the oil and its longevity (i.e. how quickly it will evaporate) will strongly influence the impacts that can be expected in a particular habitat.

Overview

Toxicity

Toxicity is defined as, "The inherent potential or capacity of a material to cause adverse effects in a living organism" (Rand and Petrocelli 1985). Another way of saying this is that no chemical is completely safe, and no chemical is completely harmful. Concentration, duration of exposure, and sensitivity of the receptor organism will all determine the toxic effect.

Sensitivity

Sensitivity to toxic compounds varies greatly by species, by life stage within a particular species, and by individual. In general, younger stages are more sensitive than adults (for example, eggs and larvae are often more sensitive than adult fish), but some exceptions exist (See Figure 4-1; NAS 1985).

Oil impacts between species groups vary. Though individual exceptions undoubtably exist, a broad categorization can be made for the anticipated degree of impact as follows (NAS 1985):

- Little to no long-term effects: annelids, gastropods, copepods
- Some effects: macrophytes, barnacles
- Long-term effects: corals, bivalves, decapod crustacea

Within one species, individual characteristics will also determine the degree of impact, including age, sex and contamination history. A study on kelp shrimp found that animals that had been previously exposed to naphthalene (a component of oil) had less tolerance to the compound. In contrast, pink salmon exhibited the opposite effect; fish that were previously exposed to naphthalene had significantly greater tolerance when tested later with bioassays (Rice and Thomas 1989).

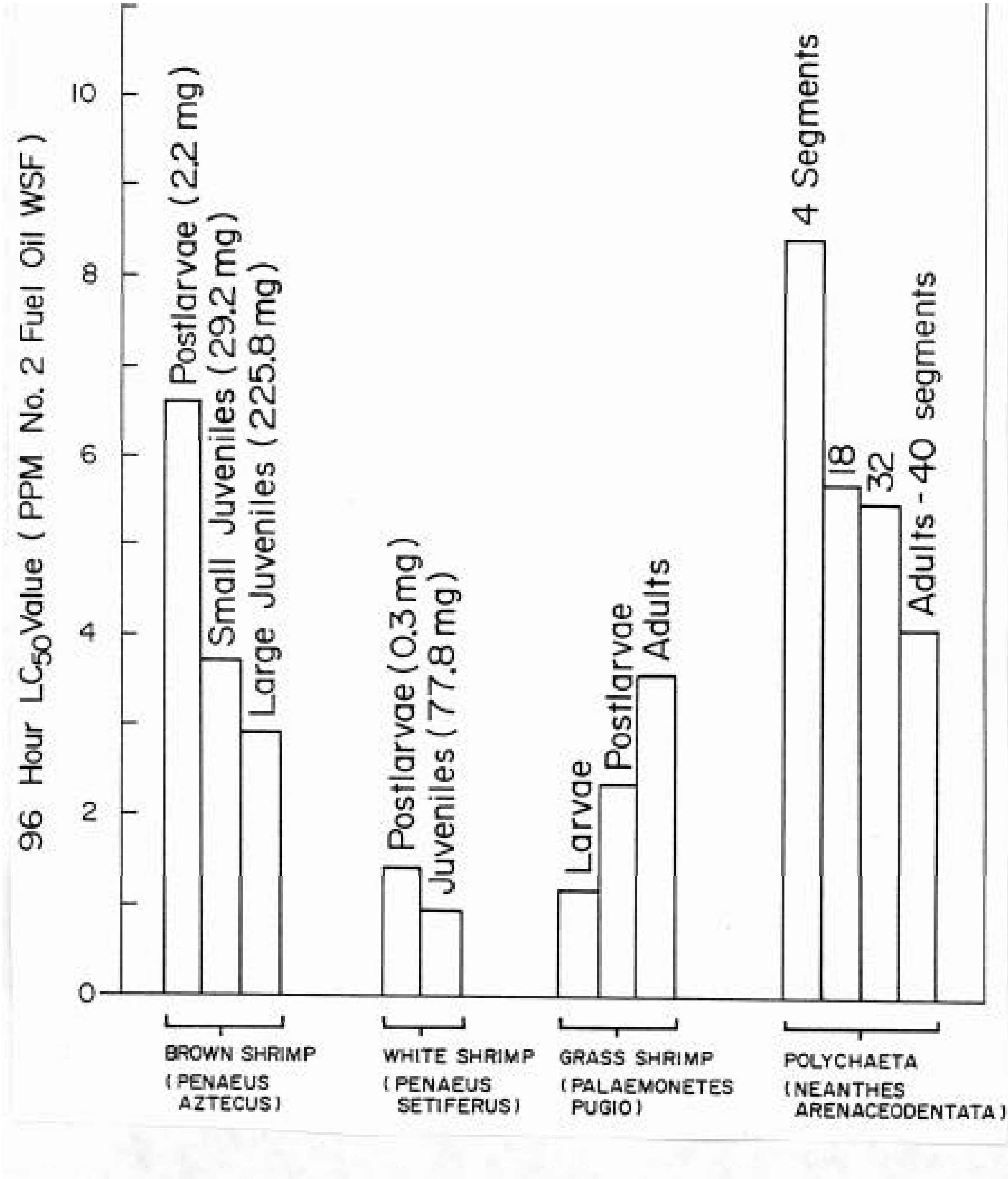


Figure 4-1. Toxicity of No. 2 fuel oil to life-cycle stages of selected marine shrimp and polychaetes. Life-cycle stages are indicated by size or segment number (NAS 1985).

Acute effects

Acute toxicity refers to immediate impacts that result in death of the organism. One acute effect of oil on shoreline organisms is the physical process of smothering (NAS 1985). Intertidal invertebrates and some plants may be especially sensitive to smothering. Acute effects can also result from the toxic components of the oil. Acute toxicity will be dependent on the toxic properties of the oil (a combination of the oil type and weathering), and the concentration and dose that the organism receives (See Figure 4-2).

Studies conducted at the *Amoco Cadiz* spill in France documented acute effects to subtidal amphipods. A reduction in biomass of approximately 40% was measured for certain amphipod populations immediately after the spill (Dauvin and Gentil 1990).

A single dose of a toxic substance at a high concentration can have the same effect as repeated doses at lower concentrations. The salt marsh plant *Juncus roemerianus* showed the same acute response to one exposure of crude oil at a concentration of 1,500 ml/m2, as to 6-10 successive spills of a concentration of 600 ml/m2 (de la Cruz et al. 1981).

Chronic effects

Some toxic effects may not be evident immediately, or may not cause the death of the organism. These are called chronic, or sublethal effects, and they can impact an organisms' physiology, behavior, or reproductive capability. Chronic effects may ultimately impact the survival rates of species affected. Chronic effects are harder to detect than acute effects and may require more intensive studies conducted over a longer period of time.

Many chronic effects result from stress responses in the physiology of an organism, such as increased metabolism, increased consumption of oxygen, and reduced respiration rate. These can be short term responses, but over extended periods of time, may cause other impacts to the organism. A common chronic response is reduced growth rates, for example in benthic organisms that live in chronically oiled sediments.

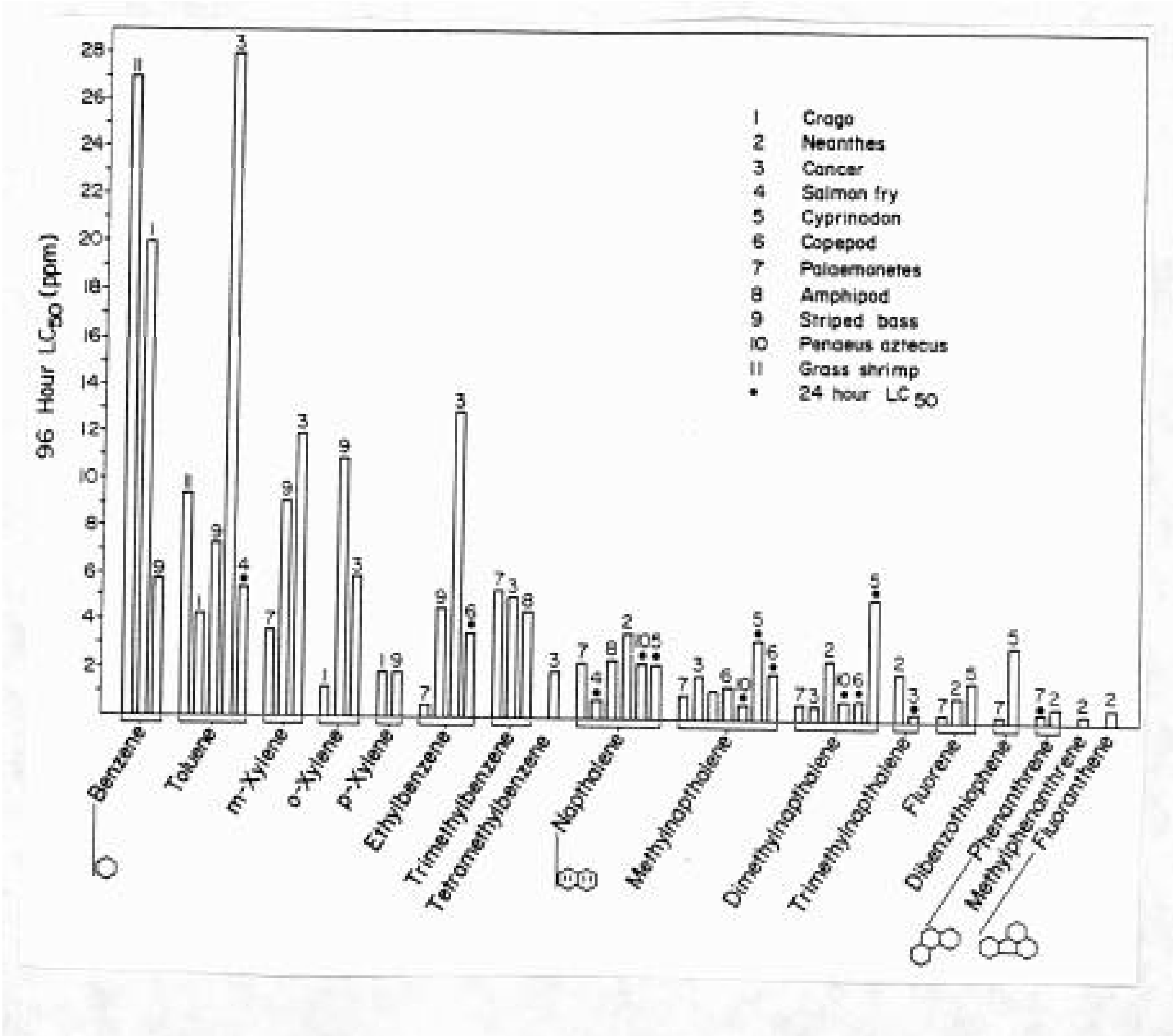


Figure 4-2. Acute toxicity (24- and 96- hour LC_{50} static tests) of some aromatic hydrocarbons for selected marine macroinvertebrates and fish (NAS 1985).

For plants, primary productivity or photosynthesis may be affected. Low concentrations of crude oil (250 ml/m2 and 600 ml/m2) affected primary productivity of *Juncus* salt marsh plants (de la Cruz et al. 1981).

Effects on reproduction from chronic exposure to oil in sediments has been documented for benthic fish species. Effects have been found for those species that spend most of their life cycle in intimate contact with contaminated sediments, for instance, flatfish such as English sole or Winter flounder (Kuhnhold et al. 1978).

Changes in behavior have also been noted for several species of fish and invertebrates when exposed to oil. Littleneck clams (*protothaca staminea*) buried themselves in sediments more slowly and at shallower depths in oiled sediments, compared with unoiled sediments. This behavior increased the clams vulnerability to predation by Dungeness crabs (Pearson et al. 1981). Reduced feeding rates have been measured for lobster larvae, adult copepods, and benthic worms (NAS 1985).

One mechanism of impact of a sublethal effect is the disturbance of an organism's chemosensory ability. Dungeness crab were found to have a decreased ability to detect littleneck clams (their prey) after exposure to crude oil. The blocking or disruption of the crabs chemosensory ability was thought to be the cause (Pearson et al. 1981)

Bioaccumulation

Bioaccumulation can be defined as the uptake of a contaminant by an organism from water directly or through consumption of contaminated food. Organisms that live in a contaminated environment, for example, mussels in oiled sediments, may appear to be healthy but still contain elevated levels of petroleum compounds in their tissue. Some components of oil can be bioaccumulated by marine organisms, particularly the group of longer lasting compounds known as polycyclic aromatic hydrocarbons (PAH).

Biomagnification is defined simply as the magnification of concentrations of a contaminant over two or more trophic levels. One concern with bioaccumulation is that contaminated organisms (such as mussels) may be eaten by higher trophic level organisms (such as otters). If biomagnification was occurring, the higher level predator (the otter) could concentrate contaminants to a level which would cause toxic effects. In the case of organisms that are harvested by humans, concerns about bioaccumulation may cause restrictions on collecting shellfish or other items consumed by humans.

Bioaccumulation may cause chronic effects to the organism involved and may also cause potential food web impacts (Widdows et al. 1987). In a field study conducted in Prince William Sound after the *Exxon Valdez*, bioaccumulation of PAH in intertidal mussels, snails, and drills was measured. However, no evidence of biomagnification was found (ERCE 1991). In the case of oil components such as PAHs, the compounds do not usually reside in the tissue for long periods of time before they are depurated. Thus, biomagnification is not usually a major concern with petroleum compounds originating from oil spills.

Bioavailability and uptake

Though all animals can take up hydrocarbons from water column directly and from food, the processes of uptake vary by species group. Macroinvertebrates can take up hydrocarbons, and the majority also metabolize them readily, with the exception of the molluscs. Within invertebrates, detritus feeding bivalves usually accumulate more hydrocarbons than suspension feeders. Depuration rates vary, but can range from a few days to much longer. Levels of hydrocarbons in fish are usually higher in liver and neural tissue than in muscle tissue. Their efficiency of uptake from food may be low (NAS 1985). Fish also have enzyme systems capable of processing aromatic hydrocarbons relatively efficiently. Contaminated sediments can provide a source of hydrocarbons to benthic fish such as flatfish.

Not all contaminants that are present in the environment will be bioavailable to organisms in the habitat. Bioavailability will be determined by a set of complex physical and chemical parameters, for instance, the amount of particulates and organic matter that may bind to the petroleum compounds, or the concentration of dissolved hydrocarbons in the water column.

Ecological effects

Some ecological effects that alter predator-prey interactions may result from a spill and result in changes in species composition or relative numbers of species in an area. This may be caused by the elimination of predators due to mortality, such as was postulated in the case of the *Tsesis* spill in Sweden. Here, an increase in growth of phytoplankton was measured shortly after the spill, and this was postulated to be a result of less than normal predation by zooplankton. Since zooplankton had experienced high mortality after the spill, this represented a direct predator-prey relationship (Johansson et al. 1980).

A similar effect may result from the fact that oil spills sometimes result in temporary closures in commercial fisheries. This also removes predatory pressure on fish populations, which may result in an increase in the fish population.

Summary

- *Resources at risk*
  resident and seasonal populations, life stages

- *Toxicity*
  varies by sensitivity of organism
  - acute - immediate, of short duration
  - chronic - sublethal, of long duration

- *Bioaccumulation*
  invertebrates accumulate hydrocarbons
  fish accumulate in liver and neural tissue, not in muscle
  biomagnification is not generally found with hydrocarbons

- *Ecological effects*
  predator - prey interactions may be affected

Open water communities

Marine birds

Marine birds can be divided into six broad categories based upon their behavior and sensitivities to oil spills. These include:

- Seabirds
  - Surface-feeding pelagic seabirds—albatrosses, petrels, fulmars, and shearwaters
  - Diving pelagic seabirds—auks, murres, murrelets, puffins, guillemots, and auklets (auks and alcids)
  - Diving coastal seabirds—pelicans, cormorants, frigatebirds, tropicbirds, gannets, and boobies
  - Surface-reeding coastal seabirds—kittiwakes, skuas, and jaegers
- Gulls and terns
- Raptors—osprey, bald eagles, and peregrine falcons
- Shorebirds—plovers, turnstones, surfbirds, sandpipers, phalaropes, and oystercatchers
- Wadingbirds—herons, egrets, bitterns, rails, ibises, cranes, spoonbills, stilts, and avocets
- Waterfowl—swans, geese, diving and dabbling ducks, mergansers, coots, gallinules, loons, and grebes

Effects of oil on birds

Bird species experience a variety of documented effects when exposed to spilled oil. These effects include:

- Fouling of plumage
- Ingestion of oil
- Effects on reproduction
- Physical disturbance

These effects are outlined below.

Fouling of Plumage. The primary direct effect from exposure to oil is fouling of plumage. Oil causes disruption of the fine structure of the small strands that form the feathers, causing loss of their water-repellent characteristics. The oiled plumage becomes matted, allowing water to penetrate to the body surface, which results in chilling and hypothermia as well as a loss of buoyancy. The ultimate cause of death of heavily oiled birds is believed to be hypothermia in most cases (Fry and Lowenstine 1985; Wood and Heaphy 1991).

The quantity of oil necessary to result in death of the individual is unknown. Tuck (1961) reported that only a small spot of oil on the belly is sufficient to kill murres, and Fry and Lowenstine (1985) reported that 3-5 ml on breast feathers was able to kill two of three Cassin's auklets tested. It has been theorized that other non-pelagic species may be much less sensitive to small quantities of oiling than the more pelagic species such as auks and murres, because they do not utilize the cold, offshore waters to the same extent. Birkhead et al. (1973) reported observations of visibly oiled gulls, guillemots, and razorbills successfully cleaning themselves after several weeks.

Ingestion of Oil. Oiled birds can readily ingest oil during preening or by consuming/scavenging contaminated prey. The effects of ingested oil include anemia, pneumonia, intestinal irritation, kidney damage, altered blood chemistry, decreased growth, impaired osmoregulation, and decreased production and viability of eggs (RPI 1988; Wood and Heaphy 1991). Hemolytic anemia is defined as the most severe effect of ingested oil; anemic birds cannot dive or forage for food and starve on beaches—even after being cleaned.

The quantity of oil required to elicit the responses outlined above is highly variable. The consumption of as little as 0.5 grams of oil has been found to inhibit certain physiological responses, while others remain intact (Clark 1984). As a result, it is not clear to what extent these physiological effects contribute to mortality following oiling, given the rapidity of death from hypothermia or drowning. It is evident, however, that ingestion of oil can contribute to the overall impacts of oil spills.

Effects on Reproduction. Direct exposure of eggs to oil has the greatest potential for damage. Previous studies have shown that small quantities of oil (as little as 1 microliter) applied to eggs reduce survival in a number of species (Crocker, et al. 1974; Holmes and Cronshaw 1977; Miller et al. 1978; Ohlendorf et al. 1978; Stickel and Dieter 1979; Peakall and Gilman 1980; Peakall et al. 1981; Clark 1984; Fry and Lowenstine 1985). Exposure during the early states of incubation are considered the most toxic. It is easy to understand how oiled adult birds can transfer toxic doses of the oil to eggs during nesting. Reports of actual impacts to eggs from oiled adults indicate there is a significant potential for reduced reproductive success in oiled birds. Reproductive success has also been shown to be affected during oil spills. Adults that are exposed to sublethal doses of oil and then ingest it may produce fewer eggs or cease laying eggs altogether. Although not documented for all bird species, there is the potential for oiled birds to experience a decline in egg production. The viability of the eggs produced following ingestion may also be reduced.

Furthermore, adult Cassin's auklets and wedge-tailed shearwaters have been shown to abandon a nesting colony even when exposed to small quantities of oil. Those adults that do attempt to nest often have a delayed or failed egg production and low hatching success. Future losses may also be realized as breeding failure may result in the birds changing mates in following years and further reducing the reproductive success. The effects of oil on other bird species are assumed to be similar to those experienced by auklets and shearwaters.

Physical Disturbance. An indirect impact of an oil spill is a result of disturbances from the physical intrusion of man during cleanup efforts. The influx of personnel and machinery to a spill site can cause a disturbance to individual birds, to breeding colonies, and to roosting areas in the vicinity of the cleanup site. Disruption of breeding will result in the greatest losses to both present and future generations.

Vulnerability for Species Groups. The overall effects of an oil spill differ considerably among bird species, due largely to differences in behavior, distribution, and reproduction. These and other characteristics are used to identify or rank bird species as to their vulnerability to oil. For ease of assimilation, the bird categories have been identified as having either a high vulnerability or low vulnerability to oil spills.

Highly vulnerable bird species are those that are closely associated or are fully dependent upon the marine environment. The following list identifies characteristics which make some bird species more vulnerable to oil spills than others:

- Frequent diving for food
- Prolonged roosting on the water
- Formation of large flocks
- Formation of dense nesting colonies in oil-spill susceptible areas
- Percent of time spent on the open ocean
- Low reproduction rates and cycles

Using this list of characteristics and observations at spills, the following bird groups are considered **highly** vulnerable to oil spills:

- Seabirds:
  - auks, murres, murrelets, puffins, guillemots, and auklets
  - storm petrels
  - pelicans and cormorants
- Waterfowl:
  - diving sea ducks (eiders, scoters), geese, loons, and grebes
- Raptors:
  - bald eagles

The majority of these birds species spend up to 24 hours associated with the water. During a spill, large numbers of these individuals may be affected as they are constantly diving for food and form large flocks while roosting on the water. During the nesting season, entire breeding colonies may be affected or destroyed as they often form dense nesting colonies in areas highly susceptible to oil spills.

Presently, the alcids are considered the most susceptible of all marine birds to spilled oil. These species occur in cold offshore waters where they often form large flocks and spend much of their time swimming or floating in the water. Pelicans as well as the other seabirds listed are considered highly susceptible due to their feeding characteristics, small populations, status as an endangered species, and low reproduction rates. These birds inhabit openwater territories, where the likelihood of encountering spilled oil is relatively high.

During migration, diving sea ducks and geese are highly vulnerable to oil spills as they use offshore and coastal marine waters for staging and overwintering. These species often occur in very large flocks in relatively exposed, open-water areas. Certain species of loons and grebes are also considered highly susceptible from oil spills even though they all do not form large flocks. The western and Pacific grebes and loon species are highly adapted to aquatic existence and rarely leave the water. They occur in open-water marine habitats during much of the year. In addition, the Pacific grebe winters in large flocks in coastal marine areas of California, Oregon, and Washington.

Bald eagles are considered to be highly vulnerable to oil spills. Although they rarely enter the water and are unlikely to be oiled, they have a small population and a very long recovery rate. The major concern regarding bald eagles is their predisposition to consuming oiled prey. As mentioned previously, ingested oil can have a multitude of effects on bird populations.

Bird species which are considered as having a **low** susceptibility to oil spills are those that are seldom associated with the open marine environment or that are highly adaptable. The following list identifies characteristics which make some bird species less vulnerable to oil spills than others:

- Rarely immersed in water
- Large percent of time spent on land or sheltered water bodies
- Prolific breeders
- Able to avoid oiled areas by shifting habitats

Bird populations which are considered to have a reduced vulnerability to spilled oil include:

- Gulls and terns
- Shorebirds
- Waterfowl
    - dabbling ducks and coots
- Wading birds
    - herons, egrets, and rails

The majority of these bird species are not as reliant on marine habitats or are fairly adjustable in their habitat preferences. Although many of these bird species utilize the marine environment, their behavior is such that it is very unlikely that they would be impacted by spilled oil.

Gulls are well known for their ability to exploit a wide range of habitats and food sources, in addition to being prolific breeders. It is theorized that gulls are readily able to avoid oil spills, since so few oiled gulls have been observed during spills. Terns are also considered to have a low risk of being directly oiled, although disturbance of nesting colonies may occur during cleanup. Shorebirds rarely encounter the water and are unlikely to be directly contaminated by spilled oil. It has been shown that shorebirds will avoid oiled areas, if there are suitable, unoiled feeding and resting areas available. Shorebirds can be indirectly impacted by loss of prey on oiled beaches, especially if the oiled area is an important feeding site on a long migration route.

Dabbling ducks are considered to have a low vulnerability to oil because they are rarely found in waters where oil spills occur. Their reliance on freshwater habitats in particular tends to reduce the likelihood of encountering oil spills. Wading birds have low vulnerability to spilled oil because they rarely enter the water other than to wade in shallow, sheltered waters. Wading birds feed by capturing prey near the surface of the water. Outside of contacting oil on their head/face during feeding or on their legs while wading, this category of birds are unlikely to be directly impacted by spilled oil.

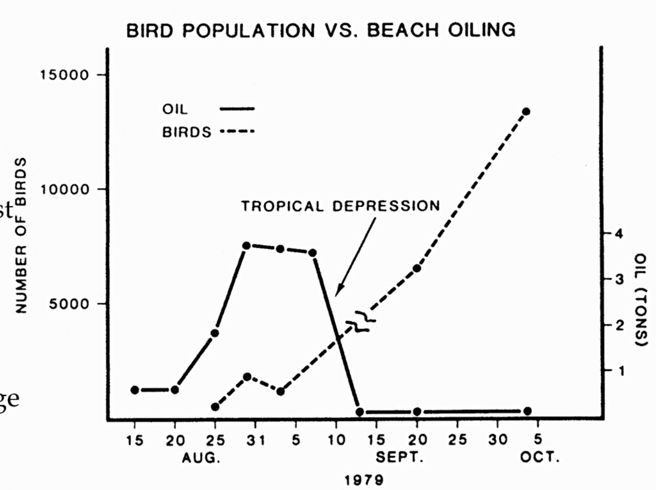
Case histories of oil spill impacts on birds. A large proportion of the knowledge we have gained regarding birds and oil are from observations at previous spills.

Ixtoc 1. On 3 June 1979, a PEMEX exploratory well, the *Ixtoc 1*, blew out in the Bay of Campeche, Mexico. This spill was not brought under control until nine months later, on 27 March 1980. An estimated 140 million bbls of oil was released during this time.

By 6 August 1979, the *Ixtoc 1* oil began impacting the Texas coastline. "Throughout the late summer and early fall of 1979, the barrier islands along the south Texas coastline were periodically impacted by oil. Padre Island and the Laguna Madre are known to be one of the most important staging and wintering areas for waterfowl, shorebirds, and colonial waterbirds in the United States (Getter et al. 1981)."

Numerous beach bird surveys were conducted. The majority of the birds identified during these surveys were shorebirds (e.g., sanderlings and willets). The surveys determined that the bird populations responded directly to oil concentrations on the beach; as oil moved on shore, birds abandoned the affected areas of the intertidal beaches and redistributed themselves into relatively clean areas, often further back on the berm tops. By the end of August, most of the normal shorebird habitat (the intertidal beach) was oiled. As a direct result of the oil presence, the total number of shorebirds declined, however, no oiled shorebirds were ever recovered, and it has been theorized that the shorebirds shifted habitats to "secondary" areas (Fig. 4-3).

Figure 4-3. Number of birds versus beach oiling, expressed in thousands of tons, on Padre Island, Texas during the Ixtoc 1 oil spill (between 15 August and 3 October 1979). Note a steady increase in the number of birds on the beach after oil was removed from the beach during the passage of a tropical depression (Getter et al. 1981).



Birds with oiled plumage never constituted more than ten percent of the total population observed during the beach surveys. The percentage of the oiled birds increased during late August, with oil coverage ranging from slight oiling of the feet to extensive (>75 percent oiling of their bodies). Royal terns were initially the species most impacted by the oil spill. By late August, "approximately 40 percent of the observed royal terns had oil on their breast feathers. However, by mid-September, royal terns avoided the high-tide line and congregated on the berm above the tar concentrations" (Getter et al. 1981). In addition, many of the wading birds were discovered to have oiled feet from feeding in oiled areas. Great blue herons, black-crowned night herons, snowy egrets, and cattle egrets were all observed to have heavy coatings of tar/oil on their feet. In a few instances, the oiling appeared to impact the bird's natural walking and flying abilities.

After natural/assisted shoreline cleanup efforts, the shorebirds reinvaded the intertidal beaches. At first, the number of birds that returned to the beach were less than before the spill, indicating that some reduction of the shorebird populations may have occurred. Over time, however, the shorebird populations increased due to the influx of migratory birds.

Only twenty-six oiled birds were recovered and turned over to rehabilitation centers during the *Ixtoc 1* spill. "Few carcasses or oil-immobilized birds were found. Carcasses that were found were mostly pelagic species. Shorebirds that succumbed to either direct or indirect effects of oil pollution were likely eaten by coyotes...that were often observed patrolling the beaches in the early morning" (Getter et al. 1981). The majority (eight) of the birds recovered were blue-faced boobies.

***Apex Houston**.* On 28 January 1986, the *Apex Houston* left Martinez, California, heading for Long Beach, California, under tow by the tugboat *Inca*. The *Apex Houston* was carrying a cargo of San Joaquin Valley crude oil. On 1 February 1986, the tow line broke, and upon boarding the *Apex Houston*, *Inca* personnel discovered that the hatch cover to the number four port tank was not in place and that a small but undetermined amount of the crude oil had been spilled.

Large numbers of oiled birds started appearing on beaches from Bodega Head to Monterey Bay on 1 February. Over the next few days, thousands of oiled birds were recovered. More than 10,500 marine birds were estimated to have been affected by this spill (Page and Carter 1986).

Two species of diving pelagic seabirds, common murres and rhinoceros auklets, were severely impacted by this spill, both in terms of the number of oiled birds recovered and the percentage of the local population of the species affected (Table 4-1). The data of Table 4-1 presents only the observations made during the 1-8 February 1988 period, in order to focus on the potential effect of the *Apex Houston* spill. The birds recovered during these eight days constitute 87.2 percent of the total of the oiled birds recovered during the months of January and February 1986.

This spill exemplifies how a very small amount of oil can have significant impacts to bird populations that are concentrated in a small local area.

Nestucca. On 22 December 1988, the barge *Nestucca* spilled 231,000 gallons of Bunker C just north of the Columbia River (Yaroch 1991). More than 3,000 live birds were recovered from Washington shorelines and turned in for treatment; 2,000 of these eventually died. Over 6,000 dead birds were observed along the shoreline. Common murres made up nearly 80 percent of the oiled birds recovered during this spill. Grebes and scoters were also significantly impacted (Yaroch 1991).

In Canada, nearly 3,600 seabirds were collected from the west coast of Vancouver Island. As in Washington, common murres were the major victims of this spill, making up 42 percent of the recovered birds. Cassin's auklets made up 32 percent of the oiled species (Harding and Englar 1989).

***Exxon Valdez*.** On 24 March 1989, the oil tanker *Exxon Valdez* ran aground in Prince William Sound, Alaska, spilling approximately 11.3 million gallons of Alaskan north slope crude oil. Over the next two months, the slick encompassed approximately 25,000 km^2 of coastal and pelagic waters, home to approximately 500,000 marine birds (Piatt et al. 1990).
Following the initial notification, the International Bird Rescue Research Center (IBRRC) established four rehabilitation centers for impacted birds. During the course of their six months of operation, 1,630 oiled live birds representing 71 different species were captured and brought to the IBRRC rehabilitation facilities. An additional 36,500 carcasses were also recovered from the impacted area (Holcomb 1991; Wood and Heaphy 1991). The actual

number of birds recovered only represents a small fraction of the birds actually killed, which could range up to 300,000.

Table 4-1. Estimated number of birds debilitated or killed by oil between 1 and 8 February 1986 from Salmon Creek, Sonoma County to Point Lobos, Monterey County (from Page and Carter 1986).

Species	Alive and Sent to Rehabilitation Centers	Estimated Total Dead on Beaches	Lost at Sea	Total
Loons	123	148	—	276
Small grebes	9	106	—	115
Western/Clark's grebes	155	313	—	468
Unidentified grebes	19	—	—	19
Scoters	61	222	—	283
Common murres	2,924	3,595	969	7,488
Auklets/murrelets	9	168	29	206
(Cassin's suklets)*		(140)	(29)	(169)
Rhinoceros suklets	30	1,201	335	1,566
Other species/ Unidentified birds	29	127	—	156
TOTAL	**3,364**	**5,880**	**1,333**	**10,577**

* The number of Cassin's auklets within the auklets/murrelets category is in parentheses.

Individuals from the widespread populations of ducks and alcids that existed at the spill site were the most common type of dead birds recovered. Several of the more sparsely distributed species, such as bald eagles, puffins, cormorants, loons, murrelets, shearwaters, fulmars, and petrels, were also impacted in large numbers during this spill (Table 4-2).

It has been estimated that ten percent of the existing common murre population that previously existed in the Gulf of Alaska was affected and that more than 50 percent of the population within Prince William Sound was killed (Piatt et al. 1990).

This was the first spill at which large numbers of eagles were oiled. It was estimated that 5,000 eagles occurred in the oiled area. In 1989, 153 bald eagle carcasses were recovered. Thirty-nine live, oiled bald eagles were sent to rehabilitation centers, of which 15 expired. As a result of this problem, a 1990 Eagle Capture program was initiated as a joint effort between Exxon and the U.S. Fish and Wildlife Service.

During this study, 113 bald eagles were captured and examined for signs of oiling and for general health conditions. Of those captured, 74 were immediately released because they were not oiled and were generally healthy (Figs. 4-4 and 4-5). Thirty-eight of the birds were considered oiled to various degrees (light to heavy), however an additional 24 lightly oiled bald eagles were released immediately. Consequently, 87 percent (98) of the captured birds met release criteria. Fifteen of the captured eagles required further medical treatment and were transported to a rehabilitation center (Gibson 1991).

Observations by the capture teams indicated that the bald eagles were not hunting in oiled areas. During capture efforts, the eagles would ignore floating fish snares if they were set too near an oiled area or shoreline.

Table 4-2. Birds killed by the *Exxon Valdez* spill which were retrieved from Prince William Sound (PWS), Kenai Peninsula (KP), Barren Islands, Alaskan Peninsula (AP), and Kodiak between 25 March and 9 June 1989 (Piatt et al. 1989).

	PWS	**KP**	**Barren Islands**	**AP**	**Kodiak**
Number Retrieved	2,793	4,501	1,912	4,258	6,332
			Percent Retrieved by Bird Type		
Murres	14.9	63.2	88.4	91.1	90.7
Sea ducks	25.2	8.7	0.5	1.5	0.5
Murrelets	11.8	4.8	3.7	1.5	2.3
Grebes	11.7	1.8	0.2	0.3	0.2
Loons	8.9	2.0	0.3	0.4	<0.1
Others	27.5	19.5	6.9	5.2	>6.2

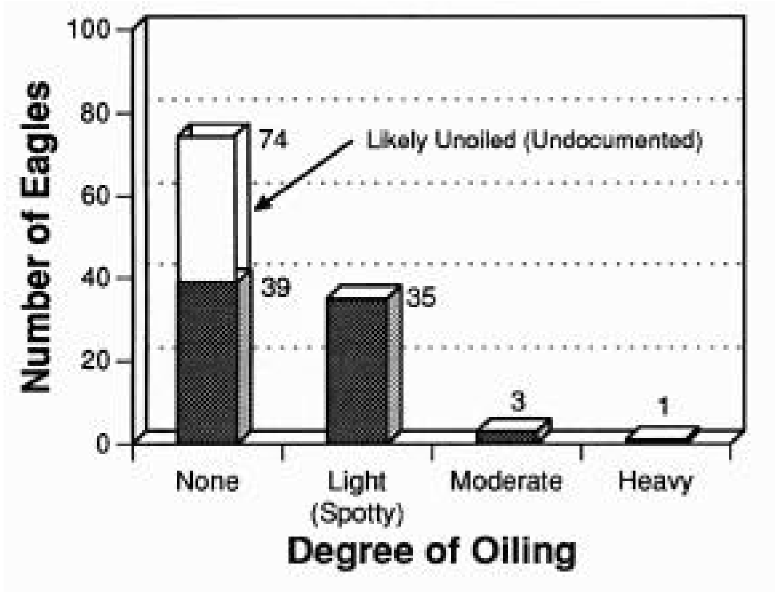


Figure 4-4. The degree of oiling for 113 eagles examined during the 1990 Eagle Capture Program as part of the *Exxon Valdez* monitoring effort (Wood and Heaphy 1991).

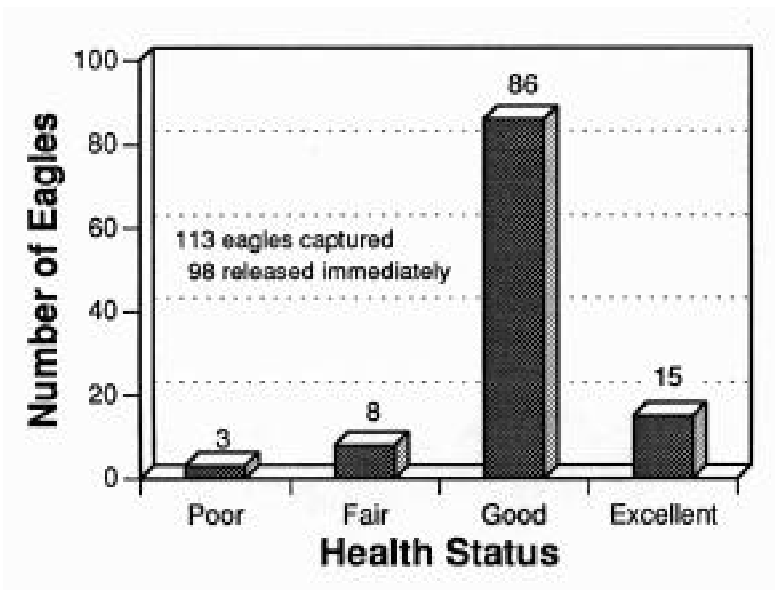


Figure 4-5. The health status of 113 eagles examined during the 1990 Eagle Capture Program as part of the *Exxon Valdez* monitoring efforts (Wood and Heaphy 1991).

Marine Mammals

Marine mammals have a number of behavioral, anatomical, and physiological adaptations that enable them to spend most or all of their lives in the ocean. As a group, they have evolved to be able to utilize nearly every marine environment along the open waters of the world. Along the North American continent, the focus of this report, many diverse marine mammal species exist in a wide range of ecosystems, from the warm, tropical waters of the Atlantic and Pacific Oceans, to the cold, often ice-covered waters of the Arctic Ocean.

In this discussion, pertinent life history data, habitat range, population status, and behavior are given for each of the following mammal groups.

- Cetaceans (whales, dolphins and porpoises)
- Pinnipeds (seals, sea lions, and walruses)
- Sea otters

Primary emphasis is on defining the interaction and effects of oil on marine mammals, which occurs primarily in three ways:

1) direct surface fouling;
2) direct and indirect ingestion with the affects of bioaccumulation; and
3) inhalation of the toxic vapors released from the petroleum hydrocarbons as they evaporate.

Additionally, any behavioral aspects of the species groups which would increase the risk of contamination are identified. A brief synopsis of all expected effects of petroleum hydrocarbons on marine mammals is given in Table 4-3; primary effects expected for oil exposure by all marine mammals are presented first, and unique effects, by marine mammal type, are listed next.

Table 4-3. List of common effects exhibited by marine mammals when exposed to oil.

	Inhalation	Surficial Contact	Ingestion
Marine Mammals (Pertains to All Species)	- Absorption into the circulatory system. - Mild irritation to permanent damage to respiratory surfaces and mucosal membranes.	- Irritation to eyes and skin. - Increased metabolism. - Inhibits thermoregulation.	**Direct Consumption** May result in irritation/destruction of: - intestinal linings. - organ damage. - neurological disorders. - bioaccumulation of toxins. **Indirect Consumption** May occur through grooming efforts. May result in: - transferral of toxins to young via lactation.
Whales and Dolphins		Little or no effect is expected. - May result in a temporary reduction in feeding efficiency for baleen whales.	- Direct consumption unlikely to occur. Exceptions include killer whales and gray whales due to their dietary preferences.
Seals, Sea Lions, and Walruses		- Destroys insulative property of fur. - Young and immature are most at risk.	- Direct consumption unlikely to occur. - Indirect consumption may occur from grooming pups.
Sea Otters	May also affect: - lungs and other organs. - nervous system	- Destroys insulative property of fur. - Young and immature are most at risk. - Often results in the death of oiled individuals.	- Direct consumption unlikely to occur. - Indirect consumption through obsessive grooming behavior has been documented causing degenerative liver lesions, kidney failure, endocrine imbalances, diarrhea, and death.

Cetaceans

Cetaceans, an order composed of whales, dolphins, and porpoises, are warm-blooded relatives of their terrestrial counterparts. Evolutionary forces have altered their four-legged bodies to their present stream-lined, nearly hairless forms. Fore and hind limbs have been replaced with flippers/fins, and broad, flat tail flukes. Thick layers of subcutaneous fat have replaced furred pelts, being a more efficient thermoregulatory aid in their watery environment.

Two suborders of cetaceans exist today:

1) Mysticeti or baleen whales. Large whales that travel in loose associations and have well established migration routes. With few exceptions, these animals have an unlimited, often worldwide, habitat range.

2) Odontoceti or toothed whales, dolphins, and porpoises. This family exhibits a broad range in size and contains the majority of the animal species within the order Cetacea. These toothed whale and dolphin species are very gregarious, often forming large, stable groups or pods with strong kinship bonds.

Table 4-4 lists both the common name and scientific names for the baleen and toothed whales, dolphins, and porpoises found in North American waters. Additionally, the global range, population estimates, and status of the species are listed. As can be seen from Table 4-4, the majority of the baleen whales exist worldwide, and are considered endangered by the United States Endangered Species Act. Additionally, toothed whales and dolphins have worldwide geographical ranges, with a few notable exceptions. However, the majority of the toothed whales, dolphins, and porpoises are not on the endangered species list.

Effects of Oil on Cetaceans

In general, whales, dolphins, and porpoises are considered to have the ability to detect and avoid oil and other petroleum hydrocarbons. Numerous studies were conducted on dolphins regarding their detection abilities (Geraci et al. 1983; Smith et al. 1983; St. Aubin et al. 1985). In all instances, the representative test animals were able to identify the presence of the pollutant and actively avoided contact with surface slicks. Other whales and dolphins

Table 4-4. Geographic range, population estimates, and status of cetaceans common to North America[1].

		Geographic Region	Population	Status*
ORDER Cetacea				
SUBORDER Mysticeti (Baleen whales)				
FAMLY Balaenida (Right whales)				
Bowhead whale	*Balaena mysticelus*	Worldwide	8,500[a]	endangered
Northern right whale	*Eubalaena glacialis*	Worldwide	3,100-3,200	endangered
FAMILY Balaenopteridae (Rorqual whales)				
Blue whale	*Balaenoptera musculus*	Worldwide	11,700	endangered
Brydes's whale	*Balaenoptera edeni*	Worldwide	30,000-56,000	not listed
Fin whale	*Balaenoptera physalus*	Worldwide	105,000-122,000	endangered
Humpback whale	*Megaptera novaengliae*	Worldwide	9,500-10,000	endangered
Minke whale	*Balaenoptera acutorostrata*	Worldwide	315,800-331,800	not listed
Sei whale	*Balaenoptera borealis*	Worldwide	48,000-63,000	endangered
FAMILY Eschrichtiidae				
Gray whale	*Eschrichtius robustus*	N.E. Pacific	21,000	endangered
SUBORDER Odontoceti (Toothed whales, dolphins, and porpoises)				
FAMILY Monodontidae				
Beluga	*Delphinapterus leucas*	Worldwide	40,000-55,000	not listed
Narwhal	*Monodon monoceros*	Worldwide	29,000[a]	not listed
FAMILY Delphinidae				
Atlantic white-sided dolphin	*Lagenorhynchus acutus*	W.N Atlantic	24,000	not listed
Bottlenose dolphin	*Tursiops truncatus*	Worldwide	24,240-33,840[a]	not listed
Common dolphin	*Delphinus delphis*	Worldwide	+1,000,000	not listed

Table 4-4. Continued.

		Geographic Region	Population	Status*
FAMILY Delphinidae (continued)				
Hawaiian spinner dolphin	*Stenella longirostris*	Worldwide	1.1 million	not listed
Killer whale	*Orcinus orca*	Worldwide	1,000[a]	not listed
Long-finned pilot whale	*Globicephala melaena*	Worldwide	13,000-50,000[a]	not listed
Pacific white-sided dolphin	*Lagenorhyncus obliquidens*	Worldwide	50,000[b]	not listed
Risso's dolphin	*Grampus griseus*	Worldwide	10,000[a]	not listed
Spotted dolphin	*Stenella spp.*	Worldwide	3.3 million[b]	not listed
Striped dolphin	*Stenella coeruleoalba*	Worldwide	2.3 million[b]	not listed
FAMILY Phocoenidae (Porpoises)				
Dall's porpoise	*Phocoenoides dalli*	Worldwide	1.4-2.8 million	not listed
Harbor porpoise	*Phocoena phocoena*	Worldwide	18,000[a]	not listed
Vaquita	*Phocoena sinus*	Gulf of California (entire population)	200-300	endangered

1 Modified from Geraci and St. Aubin (1990).

* As listed in the United States Endangered Species Act.

a Estimates for North American populations.

b Estimates for Eastern North Pacific populations.

probably would also be able to detect and avoid oil contamination. However, in their natural environment, there are many instances where whale and dolphin individuals swam directly into an affected area, not seeming to notice the oil slicks. The question of lethal and sublethal effects of oil on whale, dolphin, and porpoise species has not been successfully answered. The historical observations during actual spills on the effects of oil spills on whales, by species, are summarized in Table 4-5.

Direct Surface Fouling. Direct oiling of whales, dolphins, and porpoises is not considered a serious risk to the thermoregulatory capabilities of these animals. After extensive studies, Geraci (1990) determined that direct surface fouling poses little if any problem to these animals. Any irritation that were to occur would rapidly recover due to a resistant dermal shield found in whale, dolphin, and porpoise skin. This dermal shield has been defined as an extraordinarily thick epidermal layer which is highly effective as a barrier to the toxic, penetrating substances found in petroleum.
The baleen whales, which use baleen plates to feed, presents an area of concern regarding surface fouling. Could these plates became fouled? and if so, Would these individuals survive the oiling? It is possible that oil residues would adhere and clog the baleen plates, thereby interfering with the affected individual's feeding. To date, only one baleen whale has ever been reported as having its baleen plates fouled by oil (Brownell 1971). In an effort to determine the degree of impact, a series of tests were conducted to detect the effects of various petroleum hydrocarbons on isolated baleen plates (Braithwaite 1983; Geraci and St. Aubin 1982; 1985). The tests show that even the heaviest of petroleum compounds may only temporarily reduce a baleen whales feeding efficiency. Table 4-3 lists the expected effects of baleen fouling.

Inhalation. Geraci (1990) has theorized that "a greater threat to whales or dolphins is not the thick murky residue [of surface slicks], but the invisible gaseous compounds that escaped from it." Inhalation of the toxic volatile fractions from fresh oil spills may produce a variety of problems for these air-breathing mammals. This pathway of exposure would be a threat primarily during the first few days after the spill occurs. Table 4-3 identifies the effects that may be encountered by whales and dolphins inhaling the volatile fractions from an oil spill.

Table 4-5. Historic interactions and impacts of whales and dolphins with oil[a].

Date	Location and Source	Oil Type and Quantity	Species	Impacts
Feb. 1969	Santa Barbara, CA; Union Oil Well	Crude oil; >30 x 10^6 gal	Gray whales Pilot whales Sperm whales Common dolphins White-sided dolphins	Sixteen stranded whales and dolphins were recovered. No causal relationship was established.
Apr. 1970	Alaska Peninsula; Source unknown	Diesel fuel; quantity unknown	Killer whales	One sick and one dead killer whales were observed. No examination was conducted to determine causal relationship.
1974	Japan; Source unknown	Bunker C; 11.3 x 10^6 gal	Porpoise	One dead porpoise found.
Oct. 1976	Aransas Pass, TX; Pipeline leak	Crude oil; 15,500 gal	Bottlenose dolphins	Dolphins swam through the oil without any apparent effects.
Dec. 1976	Nantucket Shoals; *Argo Merchant*	Bunker C; 7.9 x 10^6 gal	Fin whales Pilot whales and others	Forty-three sightings were recorded for animals in and around patches of oil. No obvious reaction was observed.
Mar. 1978	France; *Amoco Cadiz*	Crude oil; 60 x 10^6 gal	White sided dolphins Common dolphins Pilot whales	Six stranded animals were recovered. No causal relationship was established.
Sept. 1978	Matagorda Bay, TX; Boat grounding	Fuel oil; 3,000 gal	Bottlenose dolphins	Twenty dolphins were observed to be swimming through the oil without any effect.
June 1979	Gulf of Mexico; *Ixtoc-I*	Crude oil; 70 x 10^6 gal	Bottlenose dolphins Spotted dolphins	Animals were sighted in areas with oil-coated debris. The animals were apparently unaffected.
June 1979	Cape Cod, MA; *Regal Sword*	Bunker C/Fuel oil; 80,000 gal/6,300 gal	Humpback whales Fin whales Minke whales Right whales White-sided dolphins	Animals were observed feeding, surfacing, and swimming through heavy concentrations of oil.

[a] Table was developed from J.R. Geraci and D.J. St. Aubin (1990)

Table 4-5. Continued.

Date	Location and Source	Oil Type and Quantity	Species	Impacts
May 1981	Outer Banks, NC; *Hellenic Carrier*	Unknown; 3,000 gal	Porpoise	Unconfirmed report of a dead porpoise.
Mar. 1982	Rodanthe, NC; Source unknown	Tar; quantity unknown	Pilot whale	One stranded whales was recovered with a small patch of dry tar on its skin.
July 1984	Gulf of Mexico; *Alvenas*	Crude oil; >1 x 10^6 gal	Bottlenose dolphins	One dolphin was swimming in the midst of oil patches. Others were observed at the edge of the slick.
Mar. 1989	Prince William Sound, AK; *Exxon Valdez*	Crude oil; 11 x 10^6 gal	Gray whales Fin whale Minke whales Unidentified whales Harbor porpoises	The following quantities of carcasses were recovered: 25 gray, 1 fin, 2 minke, and 3 unidentified whales; 7 harbor porpoises. It is possible that these mortalities were of natural causes.
June 1990	Gulf of Mexico; *Mega Borg*	Crude oil; 4.3 x 10^6 gal	Bottlenose dolphins	Dolphins were observed to swim in the midst of oil patches while others were observed at the edge of the slicks. No observable effect was detected.

Ingestion. There are two forms of ingestion that are considered here:

1) direct ingestion or the conscious consumption of petroleum hydrocarbons; and

2) indirect ingestion of petroleum hydrocarbons through the consumption of contaminated food sources, which includes bioaccumulation.

Direct consumption of petroleum hydrocarbons is considered highly unlikely in whales, dolphins, and porpoises, and any quantity consumed is not likely to have any direct affect upon the individual. A more likely form of petroleum hydrocarbon ingestion is through the incidental consumption of contaminated food. Geraci (1990) remarks that most toothed cetaceans (with the exception of bottlenose dolphins) are predators that would not scavenge oil-killed fish and will also avoid oil-tainted fish. Baleen whales, however, are more likely to consume contaminated food sources. For most baleen whales, zooplankton comprise the majority of their diets. These small crustaceans ingest oil particles and rapidly process them. The consumption of a critical dose of petroleum hydrocarbons is a possibility for baleen whales feeding in and around an area of a fresh spill.

Marine mammals have the potential to accumulate petroleum hydrocarbons in their tissues. However, this is more likely to occur in cold environments where prey organisms, such as zooplankton or benthic invertebrates, metabolize hydrocarbons more slowly than in warmer environments (Geraci 1990; Neff 1990). Because marine carnivores generally do not assimilate petroleum compounds from food efficiently, biomagnification does not usually occur. Since invertebrates are less able to metabolize hydrocarbons than fish, mammals eating low on the food chain (such as walrus or sea otters that consume large quantities of bivalve molluscs, or baleen whales that feed on zooplankton) are more likely to accumulate hydrocarbons than are top carnivores, such as killer whales, that consume large pelagic fish (Neff 1990). To date, no sublethal effects on this animal group have ever been attributed to bioaccumulation of petroleum hydrocarbons.

Areas of Special Concern. Table 4-6 identifies the behaviors and habits which are presumed to increase the risk of exposure to petroleum hydrocarbons by whales, dolphins, and porpoises.

Table 4-6. Behaviors and habits of whales, dolphins, and porpoises that may predispose them to oil exposure.

1) Habitat Preference—Spills in ice covered waters may increase the risk of exposure due to oil entrainment within the ice, and reduced weathering of the oil. Habitat fidelity is not strong among cetaceans. If an area were affected by oil, it is assumed that the animals will simply remove themselves from the area.
2) Migration Routes—Many species participate in annual migration cycles, often through areas of oil exploration. Pelagic species are more at risk than in previous history as man's exploration activities expands into deep water areas. Additionally, many species migrate through areas of intense petroleum transportation activities, again increasing the likelihood of exposure.
3) Migration Hierarchies—Many species exhibit specific migration "pecking orders," e.g., pregnant females are first to arrive to feeding/birthing grounds, then females with calves, then immature females, then adult males, and finally immature males. This migration pattern may expose an entire section of the migrating subpopulation to a spill, adversely affecting the pod.
4) Dietary Preference—Many species exhibit restricted diets. If a species food source were affected, it may be forced to consume contaminated food or be forced to adjust its diet. However, as mentioned above, site fidelity is not strong among cetaceans and it is assumed that the animals would simply move to another, unaffected area to feed. The major concern would be for animals feeding prior to beginning a migratory journey. The stresses associated with migration preparation may adversely affect a cetacean if further stressed by a spill.
5) Social Structure—Toothed species often travel in pods, acting as a unit. As in the case of mass strandings, the herd follows the lead animal. During a spill, a whole pod, or a large portion may be adversely affected.
6) Reproduction—The reproductive success may be reduced by exposure to a spill. Pregnant females are considered most at risk to effects.
7) Natural Curiosity—Curiosity in younger animals may increase their likelihood of exposure. There are many reports of juveniles "playing" with debris on the waters surface.

Pinnipeds

Pinnipeds, an order composed of walruses, seals, and sea lions, are probably the most common and well known of all marine mammals. Like other marine mammals, they are highly adapted to life in the water; they have streamlined bodies, paddle-like fore- and hindlimbs, thick layers of subcutaneous fat, and other advantageous morphological and physiological adaptations. Walruses, seals, and sea lions are highly social and routinely leave the water to congregate on sand beaches, rocky shores, and tidal flats for resting, breeding, and birthing.

Three families of pinnipeds exist today:

1) Phocidae, the true or crawling seals;
2) Otariidae, the walking seals; and
3) Odobenidae, the walruses.

Table 4-7 lists common and scientific names of the 14 species of walruses, seals, and sea lions existing in North American waters (walruses have been divided into two sub-species). The global range and population estimates of the species are also listed. Walruses, seals, and sea lions are not included on the U.S. Endangered Species list.

Effects of Oil on Pinnipeds

All walrus, seal, and sea lion species are considered to have the ability to detect and avoid oil and other petroleum hydrocarbons. To date, no studies have been conducted on these animals regarding their detection abilities, but anecdotal data indicates that they will avoid a spill. However, in the wild, there are also many contradictory incidents where seals, sea lions, and fur seals have swam directly into an affected area, not seeming to notice the oil slicks. Numerous deaths have been related to direct and indirect exposure of seals and sea lions to petroleum hydrocarbons. Table 4-8 summarizes observations of pinniped exposure to historic oil spill events.

Table 4-7. Geographic range, population estimates, and status for pinnipeds common to North America[1].

		Geographic Region	Population
ORDER Carnivora			
FAMILY Phocidae (Crawling seals)			
Bearded seal	*Erignathus barbatus*	Canadian Arctic and Bering-Chukchi Sea	400,000+
Gray seal	*Halichoerus grypus*	E. Canada	70,000
Harbor seal	*Phoca vitulina*	New England to E. Canadian Arctic California to Aleutians	157,000
Harp seal	*Phoca groenlandica*	E. Canada	2,250,000
Hooded seal	*Cystophora cristata*	E. Canada; Davis Strait	366,000
Northern elephant seal	*Mirounga angustirostris*	California, Mexico	60,000+
Ribbon seal	*Phoca fasciata*	Bering-Chukchi Seas	100,000
Ringed seal	*Phoca hispida*	E. Canadian Arctic; Bering Sea Beaufort and Chukchi Seas	2.3 million
Spotted seal	*Phoca largha*	Bering-Chukchi Seas	225,000
FAMILY Otariidae (Walking seals)			
California sea lion	*Zalophus californianus*	Mexico to California	145,000+
Guadeloupe fur seal	*Arctocephalus galapagoensis*	Mexico	1,000+
Northern fur seal	*Callorhinus ursinus*	Pribilof Islands, San Miguel Island, Calif.	1,300,000+
Steller's sea lion	*Eumetopias jubatus*	California to the Bering Sea	221,000
FAMILY Odobenidae (Walruses)			
Atlantic walrus	*Odobenus rosmarus rosmarus*	Eastern Arctic	25,000?
Pacific walrus	*Odobenus rosmarus divergens*	Western Arctic and Alaska	160,000

1 Modified from J.R. Geraci and D.J. St. Aubin,(1990).

Table 4-8. Historical interactions and impacts of seals, sea lions, and walruses with oil[a] .

Date	Location and Source	Oil Type and Quantity	Species	Impacts
late 1940s	Antarctic; Ship discharge	Fuel oil; quantity unknown	Unspecified seals	Bloodshot eyes. Surface fouling with tarry oil.
1949	Ramsay Island, Wales; Source unknown	Fuel oil; quantity unknown	Gray seals	Pups largely unaffected by thick coating of oil. Two fouled pups drowned.
Mar. 1967	English Channel; *Torrey Canyon*	Crude oil; 30×10^6 gal	Gray seals	Three oiled seals were recovered, confirmed deaths
Jan. 1969	Gulf of St. Lawrence; Storage tank	Bunker C; 4,000 gal	Harp seals	10-15,000 seals coasted. Unspecified number of dead recovered
Feb. 1969	Santa Barbara, CA; Union Oil Well	Crude oil; $>30 \times 10^6$ gal	Harbor seals Elephant seals Cal. seal lions	Oiled seals observed. Mortalities not linked conclusively to incident.
Nov. 1969	N. Dyfed, Wales; Source unknown	Unknown; quantity unknown	Gray seals	14 oiled. Dead pups found. No causal relationship established.
Feb. 1970	Chedabucto Bay and Sable Island, N.S.; *Arrow*	Bunker C; 4×10^6 gal	Gray seals Harbor seals	150-160 seals oiled on Sable Island; 500 seals oiled in Chedabucto Bay. 24 found dead, some with oil in mouth or stomach.
Feb-Mar 1970	Kodiak Island, AK; Ship discharge	Slop oil or oily ballast; quantity unknown	Hair seals sea lions	Estimated 500 mammals contacted. No mortalities recorded.
Apr. 1970	Alaska Peninsula; Source unknown	Diesel fuel; quantity unknown	Hair seals	400 seals exhibited unusual behavior. No mortalities recorded.
Nov. 1970	Farne Islands; Source unknown	Unknown; quantity unknown	Gray seal	Yearling seal found with oil-stained pelt and crusting around mouth. Animal was otherwise healthy.
Mar. 1972	British Columbia *Vanlene*	Bunker B; 100,000 gal	Seals	Seal herds in area were unaffected.
Sept. 1973	Repulse Bay, NWT; Ship discharge	Refuse oil; quantity unknown	Ringed seals	Hunters killed 5 oil-covered seals.

[a] Table was developed from J.R. Geraci and D.J. St. Aubin (1990)

Table 4-8. Continued.

Date	Location and Source	Oil Type and Quantity	Species	Impacts
1973	Dutch coast; Source unknown	Unknown; quantity unknown	Harbor seal	Patch of oil inconclusively associated with skin lesions.
1974-1979	Cape Town, SA; Ships and industry	Chronic discharge	Cape fur seals	Fur seals lingering in polluted harbor without obvious effect.
Aug. 1974	Straits of Magellan; *Metula*	Crude oil; 14×10^6 gal	S. seal lions S. Am. fur seals	Seal lions and fur seals in the area apparently unaffected.
Aug. 1974	Coast of France; Source unknown	Fuel oil; quantity unknown	Harbor seals Gray seals	Oil in intestine of one harbor seal. Three oiled gray seals, one with ingested oil.
Sept. 1974	Pembrokeshire, Wales; Source unknown	Unknown; quantity unknown	Gray seals	Two heavily oil pups drowned when washed off beach. 25 pups and 23 adults were fouled.
Jan. 1975	Ireland; *African Zodiac*	Bunker C; 1.1×10^6 gal	Seals	Seals in the area were apparently unaffected.
Aug. 1977	Greenland; *USNS Potomac*	Bunker C; 1×10^6 gal	Ringed seals other seals	16 oiled seals were observed one month after the spill.
Mar. 1978	France; *Amoco Cadiz*	Crude oil; 60×10^6 gal	Gray seals	Two of four dead seals were coated with oil. No causal relations was established.
May 1978	Great Yarmouth; *UK Eleni V*	Heavy fuel; 1×10^6 gal	Seals	20 oiled seals were observed.
Oct. 1978	South Wales; *Christos Bitas*	Crude oil; 840,000 gal	Seals	Mortality of 16 of 23 oiled individuals.
Dec 1978	Shetland Is., Scotland; *Esso Bernicia*	Bunker C; 370,000 gal	Seals	Oiled seals were observed. No mortalities were reported.
Feb. 1979	Latvia; *Antonio Gramsci*	Crude oil; 36,500 gal	Seals	One seal killed by oil.
Mar. 1979	Cabot Str., N.S.; *Kurdistan*	Bunker C; 2.1×10^6 gal	Gray seals Harbor seals	At least 4 gray and 6 harbor seals were found dead and coated with oil. No causal relationship was established. Oiled seals were found on Sable Island

Table 4-8. Continued.

Date	Location and Source	Oil Type and Quantity	Species	Impacts
Nov. 1979	Pribilof Is., AK; *F/V Ryuyo Maru*	Fuel oil; 290,000 gal	Northern fur seals	Some oiled dead pups were found. Causal relationship was never demonstrated.
Feb. 1984	Sable Is., N.S.; Well blow out	Gas condensate; quantity unknown	Gray seals	Four oiled seals were observed on Sable Island. No mortalities were reported.
Jan. 1989	Anvers Is., Antarctica; *Bahia Paraiso*	Diesel fuel; 233,000 gal	Crabeater seals Elephant seals Southern fur seals	Two crabeater seals were affected. Elephant seals and fur seals were oiled, but unharmed.
Mar. 1989	Prince William Sound, AK; *Exxon Valdez*	Crude oil; 11×10^6 gal	Harbor seals Fur seals Stellar's seal lions	Seals were observed swimming in the oil. Thirty-one harbor seals, two fur seals, and 14 seal lion carcasses were recovered with some oil fouling.

Direct Surface Fouling. Surface fouling effects on walruses, seals, and sea lions are summarized in Table 4-3. Furred species, such as the northern fur seals, are most likely at risk during an oil spill. However, lesser furred seals and sea lions are less threatened by surface oiling. Thick layers of blubber retain the animals core temperature. Anecdotal information has shown that adult and ringed seal pups are able to survive surficial oiling without suffering from hypothermia. This fact has been attributed the thick layers of blubber in adults and the utilization of brown fat stores in newly born pups (Blix et al. 1979)

Inhalation. No studies have been conducted on walruses, seals, and sea lions regarding the effect or impact of inhaling volatile hydrocarbon fractions. It is assumed that these animals would exhibit similar effects experienced by other marine mammals.

Ingestion. There are two forms of ingestion considered here. The consumption of petroleum hydrocarbons has been implicated in numerous seal and sea lion deaths. Experimental results have revealed a wide variety of effects that may result from oil ingestion by specific species. These effects are assumed to apply to all walruses, seals, and sea lions, and they vary by the amount consumed and the composition of the ingested oil. These studies have determined that walruses, seals, and sea lions would be able to tolerate the ingestion of small quantities of oil. Symptoms related to oil ingestion by walruses, seals and sea lions range from organ diseases to permanent damage or death (Table 4-3).

Animals with a dense fur coat or pelage for insulation have two major pathways in which indirect ingestion of petroleum hydrocarbons may occur—the consumption of oil-tainted foods and by grooming oil-fouled coats. The principal diet of most seals and sea lions consist of cephalopod molluscs and fish; these prey items are not likely to accumulate petroleum hydrocarbons. However, notable exceptions do exist; walrus and bearded seals feed primarily on burrowing bottom animals which do accumulate petroleum hydrocarbons. Additionally, some seal and sea lion species in North America are also known to consume other seals (primarily pups) and birds. When oiled, furred seal and sea lion species begin grooming their coats to maintain its insulative properties. It is highly likely that these animals will ingest oil through grooming activities. Oiled pups are groomed by their mothers, thus increasing the mother's chance of indirectly ingesting petroleum hydrocarbons. Furthermore, there is also the possibility of hydrocarbon transferral to pups through ingesting their mother's lipid-rich milk.

All walrus, seal, and sea lion species are assumed to have the necessary enzymes available within their systems to "convert absorbed hydrocarbons into polar metabolites which can be excreted into urine. However, some proportion of the nonpolar fractions will be deposited in lipid-rich tissues, particularly blubber" (St. Aubin 1990a). To date, no evidence of deleterious effects related to bioaccumulation of petroleum hydrocarbons have been documented.

Areas of Special Concern. Table 4-9 identifies the behaviors and habits which are presumed to increase the risk of exposure to petroleum hydrocarbons by walruses, seals, and sea lions. These include habitat preferences, reproductive strategies, recognition and avoidance behaviors in adult females, and the impact of human activity on this animal group.

Sea otters

Sea otters are the smallest marine mammals and are related to weasels, badgers, and other members of the Mustelidae. They inhabit marine environments in rocky coastal areas from Alaska to California, although most live in Alaska. Table 4-10 identifies the current population estimates for the sea otter colonies in North America. Like other marine mammals, sea otters have streamlined bodies and broadly flattened paws for swimming. However, sea otters have no subcutaneous blubber layers and depend entirely on fur for insulation. This dense fur pelage is nearly two times as dense as found on the Phocid fur seals. Additional adaptations include modified dentition which is well suited for consuming their preferential prey, hard-shelled mussels, clams, and other macroinvertebrates.

Table 4-9. Behaviors and habits of walruses, seals, and sea lions that may predispose them to oil exposure.

1)	Habitat Preference—Habitats of choice are often within or near areas of oil exploration and transportation; the habitats include: sandy and rocky shores, fast ice, pack ice, shore leads, polynyas, and oceanic fronts. Many of these areas increase an animals risk of exposure due to oil characteristics when interacting with particular habitats. For example, pack ice, polynyas, and floe areas may entrain the oil and the cold may slow weathering. These factors would act to increase the possible duration of exposure to individual animals.
2)	Maternal Recognition—Maternal recognition may be hampered if a pup becomes oiled. This loss of olfactory recognition may result in the pup being abandoned. Oiling of nursery haulouts may result in major losses to a breeding subpopulation. Additionally, pups which are cleaned at rehabilitation centers may no longer be accepted by the mother, again resulting in abandonment.
3)	Reproduction—Contact with oil during the breeding season is thought to reduce the reproductive success of the colony. Additionally, theories suggest that exposure to oil during the breeding season may result in mass, premature delivery of pups (or spontaneous abortions) due to stresses during early delivery season in California sea lions. Fur seal and sea lion breeding males and elephant seals do not eat during the entire breeding season, thus are physiologically stressed and weak at the end of the season and more susceptible to any kind of stress or contamination.
4)	Interactions with Humans—Cleanup activity during a spill may result in abandonment of haulout areas. In certain species, pups may be permanently abandoned, while others will eventually return to their young. Walrus populations often remain in large groups, anywhere from several hundred to several thousand in one area. These groups are easily startled while on land, resulting in mass stampedes. Any oil response operations near walrus haulouts must be conducted with extreme care to avoid unnecessary encounters with large groups of animals.
5)	Thermoregulation—Furred seals are most at risk from surface oiling. Insulative properties of their thick pelage are quickly lost when oiled, resulting in a rapid heat loss. In the wild, few animals are expected to survive even the lightest oiling. Although pups are considered most at risk, experiential knowledge has shown that even extreme oiling of Phocid or Otariid pups does not always result in death.

Table 4-10. Geographic range, population estimates, and status for sea otters in North America.

Geographic Range	Population Estimate	Source
Alaska	100,000 - 200,000	Rotterman and Simon Jackson 1988
Prince William Sound	16,000	DeGange et al. 1990
Washington	260	Benz, personal communication 1991
California	2,000	
Pismo Beach to Pt. Año Neuevo	~2,000	Benz, personal communication 1991
Purisima Point	< 10	Benz, personal communication 1991
San Nicholas Island	12	Benz, personal communication 1991

The sea otters primarily inhabit rocky coastal areas near shore, although they often assemble in offshore waters. Sea otters are often found resting among the kelp canopy in nearshore waters. These kelp blades are suspected of affording protection, as well as reducing drifting during resting periods (Ralls and Siniff 1990). Intense site fidelity is often encountered by investigators; although the individuals may range from the area, they often return to a particular area. In Alaska, migrations occur as individuals travel from breeding to wintering areas; this habit is not observed in the California sea otters.

Sea otters are polygamous, with males courting females within their territorial ranges. Outside of breeding periods, the animals often associate in large groups, with designated male areas and female/female with pup areas. These associations often result in large "rafts" of individuals, often exceeding 100 individuals, all resting together on the water surface. These and other sea otter characteristics increase their risk of exposure during oil spills.

Effects of oil on sea otters

There are many examples of the devastating effects of oil on sea otter individuals and populations. Geraci and Williams (1990) have determined that the sea otter is the mammal most likely to be harmed by oil, both immediately and in the long-term. A recent report released by the U.S. Fish and Wildlife Service (1991) has estimated that 3,500 to 5,500 sea otters were killed in Prince William Sound and the Gulf of Alaska as a direct result of the *Exxon Valdez* spill.

As with other marine mammals, sea otters are considered to have the ability to detect and avoid oil and other petroleum hydrocarbons. A study by Siniff (1982) analyzed sea otter detection abilities and reaction to the presence of oil. The test animals were able to identify the oil and primarily avoided contact with surface slicks. However, during this test, the animals investigated the slick and became contaminated. In the wild, there are many instances where sea otters swam directly into an affected area, not seeming to notice the slicks. Numerous deaths have been related to direct and indirect exposure of sea otters to petroleum hydrocarbons.

Direct Surface Fouling. The greatest concern regarding surface fouling of sea otters is the effect on the animal's thermoregulatory system, regardless of age. The sea otter has little subcutaneous fat and relies almost exclusively on its thick pelage for insulation. Additionally, eyes and mucous membranes are expected to be impacted by surface fouling (Table 4-3).

Inhalation. Sea otters are affected in numerous ways by inhaling the toxic vapors of fresh petroleum hydrocarbons. The effects range from mild irritation to permanent damage or even death (Table 4-3).

Ingestion. Sea otters are at risk of direct consumption of petroleum hydrocarbons via contaminated prey, particularly molluscs. They also constantly groom their pelage, and would ingest oil during grooming. Many of the prey items are thought to rapidly process hydrocarbons, but the potential for bioaccumulation exists. The effects of oil ingestion are presented in Table 4-3.

Areas of Special Concern. Foremost is the effect of oiling on the metabolic and physiologic makeup of the sea otters. Table 4-11 outlines the areas of special concern when sea otters are at risk to petroleum hydrocarbon exposure. Additional behaviors and habits that often predispose sea otters to exposure include: habitat fidelity, grooming behavior, daily habits, and rigid metabolic requirements.

Table 4-11. Behaviors and habits of sea otters that may predispose them to oil exposure.

1) Habitat Preference—Sea otters often demonstrate excessive habitat fidelity. During the course of their life, sea otters may travel periodically, often traveling hundreds of miles, or remain in an area without leaving for extended periods. During a spill, sea otters may be endangered by remaining in their preferred habitat even with the threat of contamination. Even the presence of man may not be enough to motivate a sea otter into relocating. Animals which are physically relocated during a spill may return before response activities are completed.
Additionally, sea otters often prefer to rest within kelp canopies. It has been speculated that this behavior affords the sea otter some form of protection from predators and prevents the sea otters from drifting. The kelp canopy also entrains oil, therefore increasing the risk of exposure.

2) Metabolic Requirements—Sea otters have little subcutaneous fat; they rely entirely on their pelage for insulation. As a result, their strict metabolic requirement must be continually satisfied These small mammals must consume between 22-33 percent of their body weight per day (Costa 1978) to maintain their high metabolism. This extensive food requirement cannot be interrupted or the animal will suffer severe stress, which induces an increased metabolism, which further depletes their reserves, and so on. Any factor or force which reduces the sea otters ability to forage for food may prove fatal.

3) Grooming Behavior—Due to the extreme necessity of maintaining their pelage, sea otters expend a large portion of each day grooming their coats. An animal which becomes even slightly oiled will obsessively groom trying to reestablish the insulative properties of the fur, to the exclusion of all else, even their young. The very act of grooming tends to spread the contamination as well as increase indirect ingestion of oil. Additionally, female sea otters may spend 20 percent of their day grooming their pups; if a pup becomes fouled, the mother will not only spread the oil on the pup, but will most likely become contaminated herself as well as ingesting oil during the grooming process. In most instances, surface oiling results in the death of the individual.

4) Normal Behavior—Sea otters exhibit a vast array of normal behavioral patterns which may predispose them to surface oiling. These behaviors include: surface feeding, grooming, resting, and swimming. As a result of these behaviors, an entire subpopulation may be affected/destroyed if they encounter oil.

Table 4-11. Continued.

Feeding behavior—Sea otters forage for food by diving and returning to the surface to feed. While lying on their backs, the otter will prepare its meal (often consisting of breaking open an invertebrate's shell with rocks). Animals having to expend additional energy foraging for food in marginal feeding areas would be more affected by surface oiling as their metabolic requirements were already elevated.

Resting behavior—Sea otters often come together to form living rafts while resting on the waters surface. These rafts may contain hundreds of individuals.

Swimming—Sea otters enjoy swimming as part of their daily routine. Swimming activities are not limited to areas near their preferred habitat; sea otters may travel for several days only to return to their home. Both offshore and nearshore waters are utilized.

5) Susceptibility to Oil—Of all marine mammals, sea otters suffer the greatest effects when impacted by a spill. Pups are the most susceptible to oil as they are totally reliant upon their mothers until weaned. Animals that are already experiencing stress (dietary, physical, etc.) may succumb to oil impacts more quickly than other individuals. Physical contact with oil (through surface fouling, ingestion, or inhalation) is almost always fatal. Animals recovered for cleaning during response operations have a greater chance for survival due to initiation of new clean-up techniques utilized during the *Exxon Valdez* oil spill.

Pelagic species

Effects of oil on pelagic communities are supported by a relatively sparse body of information. This is partly because effects on pelagic biota are considered to be relatively short lived, and because the dilution factor in the open ocean is thought to rapidly reduce any toxic concentrations that may be present under an oil spill. Effects on planktonic communities are also difficult to document because effects of oil must be separated from the high natural variability and seasonality found in these systems. In addition, there are analytical problems with detecting low levels of hydrocarbon concentrations in water, and with differentiating the source of these hydrocarbons.

Pelagic ecosystems do support a number of species groups, and concerns about impacts to these are raised periodically, especially when response actions such as dispersants are considered. Pelagic resources will be discussed in the following two categories:

1. Plankton
   bacterioplankton, phytoplankton, and zooplankton

2. Fish
   adults, eggs, and larvae

Plankton

Phytoplankton. Phytoplankton are generally less sensitive to the effects of oil than zooplankton, but they do experience acute and chronic effects from oil at concentrations ranging from 1-10 mg/l (ppm). Unicellular algae can take up and metabolize both aliphatic and aromatic hydrocarbons. Sensitivity to oil varies by species, as documented by a series of studies conducted in mesocosm enclosures by Lee et al. (1987). This series of experiments measured the effects of oil on plankton communities over a period of 20 days. Certain species of phytoplankton were found to be more resistant to the effects of oil (nanoflagellates and small-celled diatoms) than other species (centric diatoms). Since the regeneration time is very short for algal cells (9-12 hours), any impacts to these populations would probably be very short-lived (NAS 1985).

Oil can affect the rate of photosynthesis in phytoplankton, and thus inhibit algal growth. However, at very low concentrations (less than 0.1 mg/l), enhancement of growth rates has been recorded (NAS 1985). Measurements of plankton taken at the *Tsesis* oil spill in Sweden (No. 5 fuel oil) found an increase in phytoplankton populations after the spill. This apparent anomaly could have been caused by high mortalities of zooplankton and thus, decreased grazing pressure on the phytoplankton population (Johansson et al. 1980).

Bacterioplankton. The bacterial component of the phytoplankton increases after an oil spill. This was measured in the *Tsesis* oil spill in Sweden, as was evidence of a rapid biodegradation of hydrocarbons in the water column (Johansson et al. 1980). Concentrations of bacterioplankton showed large increases after the addition of petroleum or its derivatives in the same mesocosm experiments discussed above (Lee et al. 1987). (Nutrients were also added to the mesocosms in these experiments).

Zooplankton. Zooplankton are quite sensitive to the effects of oil, and toxic effects can be seen at concentrations ranging from 0.05 to 9.4 mg/l (NAS 1985). This sensitivity is higher for dispersed and dissolved petroleum constituents, and less for floating oils (NAS 1985). Short term effects of oil on zooplankton include possible decreases in biomass (usually temporary), as well as lower rates of feeding and reproduction. Some species such as tintinnids may increase in abundance. This may be due at least in part to an increased food supply, since these zooplankton feed on bacteria and small phytoplankton (Lee et al. 1987). Long term effects of oil on zooplankton, such as changes in community structure, have not been found.

Zooplankton can take up oil directly from the water, from food, and by direct ingestion of oil particles. Zooplankton are thought to play a role in the sedimentation of oil in the water column. Oil droplets, as well as oil attached to particulates, can be ingested by zooplankton, and later excreted as unmodified oil in fecal pellets, which may then sink, and cause a redistribution of oil from the pelagic zone to the benthic zone (Conover 1971).

Fish

Adult fish. Adult fish do not generally experience acute mortality at oil spills, and it is rare to find fish kills after a spill, especially in open water environments. (Enclosed habitats such as marshes or lakes may concentrate oil enough to cause conditions acutely toxic to fish). Fish can take up hydrocarbons through the water column directly and through food, but there is no evidence of biomagnification of hydrocarbons in fish. There is a commonly held belief that pelagic fish can avoid contamination, but little evidence was found to support this generalization in the NAS review (1985).

There are several studies documenting effects from petroleum hydrocarbons to benthic fish species. Many of these studied species such as flatfish that live in intimate contact with chronically contaminated sediments. Pelagic fish species are less likely to come in contact with dissolved hydrocarbons at toxic concentrations from oil spills except for short time periods, and are thus unlikely to experience acute or chronic effects.

Fish eggs and larvae. Fish eggs and larvae experience toxic effects at low concentrations of hydrocarbons, ranging from 1-10 ppm (Kuhnhold et al. 1978). In most cases, eggs and larvae are more sensitive than adults, though some exceptions exist. For example, pink salmon eggs were found to be very tolerant to benzene and and water-soluble petroleum (Moles et al. 1979). A study of eggs and larvae of winter flounder found significant decreases in viable hatch of eggs when exposed to 100 ppb No. 2 fuel oil during gonad maturation, fertilization, and incubation. Larvae were found to be more sensitive than eggs (Kuhnhold et al. 1978).

Summary

1. Plankton
    a. Short-lived effects (of duration one month or less)
    b. Zooplankton are more sensitive than phytoplankton

2. Fish
    a. Limited impacts to adults
    b. Eggs and larvae are more sensitive

<u>Note</u>: Effects on pelagic communities are difficult to document due to high seasonal and natural variability

Nearshore communities

Intertidal

Since the intertidal zone is an area often impacted by oil that strands on shorelines, intertidal resources and how they are valued will directly impact many decisions about shoreline cleanup. Intertidal biota can be categorized into the following groups:

1. *plants*
   including algae and wetland plants
2. *infauna*
   animals that live buried in sediments
3. *epifauna*
   animals that live on the sediment surface or attached to rocks
4. *fish*

Plants

The main plants in the intertidal zone are the attached macroalgae. Though macroalgae may be subject to smothering by oil, they can be quite resilient and survive even heavy oiling. A survey of shorelines done after the *World Prodigy* spill in Narragansett Bay in 1989 noted few dead plants, even in heavily oiled areas. However, some short term effects on reproduction of two species of *Fucus* were documented. These lasted only for a period of less than one month after the spill (Thursby et al. 1990).

At the Santa Barbara blowout in 1969, shoreline surveys were conducted using transects along which intertidal algae were identified. The results of this survey were difficult to interpret since there was a strong confounding of the impacts from oil impacts with severe storms and increased freshwater runoff during the time period immediately after the blowout (Foster et al. 1971). Observers noted that surf grass (*Phyllospadix*) growing in the intertidal zone was heavily oiled at some sites, and that these plants turned brown and died (Foster et al. 1971).

NOAA studies of intertidal communities impacted by the *Exxon Valdez* spill in Alaska found that attached macroalgae, specifically *Fucus* survived oiling at numerous sites, but were heavily impacted by hot water washing of shorelines to remove oil (Houghton et al. 1991).

Infauna

Polychaetes and other burrowing invertebrates can play an important role in the biodegradation of residual oil in sediments. Lugworms (*Arenicola*) were tested in a lab with contaminated sediments from the *Arrow* spill of bunker C oil that occurred in Nova Scotia in 1970. Sediment reworking by lugworms substantially reduced amounts of hydrocarbon in sediments, probably by the mechanisms of aerating soil and by providing an environment conducive to the growth of bacteria in their tubes. *Arenicola* could not survive in sediments with concentrations of hydrocarbons of 600 ug/g (ppm) or greater (Gordon et al. 1978).

Oligochaetes, especially species such as *Capitella capitata,* are known as opportunistic species that are commonly found in polluted areas. They colonize oiled sediments at high densities, as was observed after the *Florida* spill in West Falmouth, Massachussetts in 1969. At this site, *Capitella* was measured at high densities in oiled areas 7 months after the spill (Sanders 1978).

Copepods appear to be one group of crustaceans that are less sensitive to oil. A field experiment using Prudhoe Bay crude oil added to mudflats in Valdez, Alaska did not impact populations of three species of copepods when monitored for 30 days (Feder et al. 1990).

Clams, in contrast, often show long-lasting impacts from oil contamination, partly because they usually inhabit fine sediments in low-energy environments where oil is likely to be slow to weather and therefore remain for long periods of time. Populations of *Mya arenaria,* a soft shelled clam, were studied six years after the *Arrow* spill in Nova Scotia (Gilfillan and Vandermeulen 1978). Clams from areas still contaminated with oil had concentrations of hydrocarbons in their tissue of up to 200 ug/g (ppm).

Clam populations from oiled areas had fewer total numbers, fewer mature adults, and a 1-2 year lag in tissue growth, compared with clams from a control, unoiled population.

These soft-shelled clams were thought to be particularly sensitive to the adverse effects of oiling since their physiology makes them unable to completely close their shells. This means that the clam's mantle and gill surfaces are always exposed to sediments and interstitial water, and thus, to any contaminants in those media.

Epifauna

Epifauna includes attached organisms such as mussels and barnacles, as well as motile organisms such as snails and other gastropods and crabs. A study from the Arthur Kill in New Jersery following a spill of No. 2 fuel oil in 1990 found both acute and chronic effects on fiddler crabs (*Uca Pugnax*). Chronic effects resulted in behavior changes that were significantly different from control crabs, and which would detrimentally affect the crabs' ability to survive and compete (Burger et al. 1991).

Mussels (*Mytilus edulis*) have been observed to survive heavy oiling without apparent acute effects in Alaska. They are frequently used as indicators of bioaccumulation for various contaminants, partly because the species occurs widely, and is therefore a convenient test organism. Mussels subjected to chronic, repeated exposures of hydrocarbon fractions of diesel oil were found to have reduced feeding rates and food absorption efficiency (Widdows et al. 1987).

Barnacles, like other crustacea, are acutely sensitive to oil and often experience high mortality rates when impacted by oil on shorelines. At the Santa Barbara spill, high mortalities were observed for intertidal barnacles (*Chthamalus fissus*) (Foster et al. 1971).

Fish

Concerns about impacts from oil contamination to fish in the intertidal environment usually involve species that use the intertidal habitat for spawning. This includes Pacific herring, fish that spawn on rocky substrates, or on fronds of *Fucus* or other algae growing on rocky substrates. Spawning herring populations were a concern in *Exxon Valdez* in Alaska, and important commercial stocks spawn in areas such as San Francisco Bay.

A study comparing herring eggs from oiled sites with herring eggs from unoiled sites in Prince William Sound found no statistically significant differences in viability of larvae or survival rates for the two groups of eggs. The study did find an overall effect on biology of eggs from oiled sites, including a younger age of hatch from oiled sites. Confounding factors in this study were the patchy distribution of oil at the impacted sites, and temperature and depth differences (TRS 1990).

Other intertidal spawners that have been of concern at oil spills include surf smelt and pink salmon.

Summary

1. Plants
   Macroalgae are quite resistant to effects of oiling
   Wetland plants are susceptible, but effects vary

2. Infauna
   a. Some invertebrates survive in heavily oiled sediments, including copepods, polychaetes, oligochaetes.
   b. Polychaetes may facilitate biodegradation processes.
   c. Buried bivalves are susceptible to impacts from oiling, and often bioaccumulate contaminants.

3. Epifauna
   a. Mussels, and other attached bivalves often survive oiling, but also bioaccumulate
   b. Many crustaceans, including barnacles and crabs, are sensitive to acute and chronic effects of oiling

4. Fish
   Main concerns are for intertidal spawners

Subtidal

Introduction

Nearshore subtidal habitats can include shallow, soft bottom communities such as those found in enclosed bays, as well as eelgrass beds and offshore kelp communities. Subtidal habitats are often only lightly affected by oil spills, if at all.

Much of the scientific literature on the effects of oil on soft bottom communities comes from studies conducted near offshore oil drilling rigs and platforms. While these give some indication of the potential effects of petroleum hydrocarbons, they are more indicative of ongoing, chronic releases, typical of a continuous source of hydrocarbons rather than a single event more typical of an oil spill. However, repeated, long term impacts may be important to consider in harbors and areas with heavy vessel traffic.

Eelgrass beds and kelp beds are of special interest because of their high habitat value for marine organisms, including their use as nursery areas for many species. These habitats are, in most cases, not impacted by oil spills, but can be impacted by cleanup activities.

Effects on submerged benthic habitats

Soft bottom, fine sediments. A study conducted by Gray et al. (1990) investigated ecological effects on benthic communities near two drilling rigs in the North Sea, one in operation for many years, and another recently constructed. Changes in the diversity and number of species were noted in the area within 500-1000 m of the rigs. Opportunistic species were more dominant in these areas. Initial impacts of the newly constructed rig included an increased abundance of some species, and changes in the presence and absence of rare species.

An experiment was conducted in subtidal soft bottom habitats in Norway. Field plots were treated with low level exposures of oil and compared with control plots. One result was a significant decrease in colonization by amphipods in the oiled plots. This could have been the result of mortality of newly settled larvae or juveniles, or of avoidance by adult amphipods (Bonsdorff et al. 1990).

Studies conducted ten years after the *Amoco Cadiz* spill examined populations of several species of peracarid amphipods in different subtidal habitats (Dauvin and Gentil 1990). Immediately after the spill in 1979, heavy mortalities of amphipods occurred, with the greatest short term impacts in areas with fine sediments. Since these amphipods do not produce pelagic larvae, the researchers were interested to find out if the populations had been able to recover to levels similar to those measured prior to the spill. Their conclusions were that most populations had recovered after ten years, with the greatest differences seen in the fine sediment habitats.

Subtidal stations monitored after the *Florida* spill in Massachusetts in 1969 were found to be only lightly impacted by oil and showed little variation in species composition or density during a three-year period after the spill (Sanders 1978).

Seagrass beds. Seagrass beds occur both intertidally and subtidally. Seagrasses in subtidal beds are rarely impacted by oil spills, since they usually do not come in direct contact with the oil, while intertidal plants are at greater risk of oiling. In Santa Barbara, after the blowout in 1969, intertidal surf grass (*Phyllospadix torreyi)* turned brown and died after oiling (Foster et al. 1971). At the *Amoco Cadiz,* "almost no" effects were found on a partially oiled seagrass bed of *Zostera marina*. The main impacts to seagrass beds appeared to be with the associated fauna (Zieman et al. 1984).

One reason why seagrasses appear to be less vulnerable to oil impacts is that 50-80% of their biomass is in their rhizomes, which are buried in sediments, thus less likely to be adversely impacted by oil. Thus, even if the fronds are affected, the plant may still be alive and able to regrow (Zieman et al. 1984).

Shallow seagrass beds in tropical habitats, composed of *Thalassia sp.* were impacted by a spill in Puerto Rico in 1973. Strong winds and wave action in shallow waters was thought to carry oil into the vegetation, causing the plants to die. Subsequently, erosion increased in areas with dead plants. Renewed plant growth was observed between one and two years after the spill (Nadeau and Bergquist 1977).

Treatment impacts. Sometimes, the main impacts to seagrass beds during a spill are physical impacts associated with response activities. Several authors have suggested that hot water washing of intertidal shorelines may move oil into subtidal areas, potentially impacting seagrass habitats. This has been mentioned in connection with the *Exxon Valdez* in Alaska (Houghton et al. 1991) and at Santa Barbara (Foster et al. 1971).

At Fidalgo Bay, Washington, a refinery pipeline spill in 1991 impacted a shallow bay with extensive eelgrass beds. Though all efforts in spill cleanup attempted to protect the eelgrass, it was thought that outboard engines on small boats used as part of response activities may have cut some of the grass blades.

Kelp beds. Offshore kelp beds are similar to eelgrass beds in that they support extensive benthic and pelagic communities and serve as nursery grounds for numerous species. While the benthic community beneath the kelp is rarely impacted by oil spills, the kelp fronds often float on the water surface and may become oiled or entrain oil. Observers have noted, however, that oil rarely sticks to kelp fronds in the water.

A study conducted after the *World Prodigy* spill in Narragansett Bay in 1989 examined two species of subtidal kelp that had been studied prior to the spill. For both species, *Laminaria saccharina* and *L. digitata,* oiling had no effect on growth rates, or on general condition of the plants.

Observations were made by divers in *Macrocystis* beds offshore of areas impacted by the 1969 spill in Santa Barbara. No evidence of oil impacts to benthic habitats in kelp beds was observed. Oil was contained on the surface in floating fronds, but did not stick to the plants (Foster et al. 1971).

Treatment effects. At the *Tenyo Maru* spill, which occurred off the Pacific coast of Washington in 1991, *Nereocystis* (bull kelp) beds located just offshore were observed to be containing floating oil at the surface amongst floating fronds. Based on the concern that this oil could pose a threat to sea otters, it was proposed that the kelp be cut at the base. This proposal was considered and rejected on the basis that kelp removal would adversely impact the associated benthic and pelagic communities during their summer growing season.

Summary

1. Soft-bottom communities
   a. Chronic impacts can occur from repeated dosages (such as near drilling rigs).

   b. Oil spills have limited impacts subtidally, though some sensitive species (amphipods) may show long-term effects.

2. Seagrass beds
   Usually not impacted if subtidal, treatments can adversely affect these habitats.

3. Kelp beds
   Usually little-to-no impact on these habitats

Seafood contamination

Background

An issue of concern which arises in nearly every oil spill incident of any significance is that of contamination of seafood resources in the affected area. The importance of an explicit consideration of potential impacts cannot be overstated, as the implications to diverse interests are substantial. Real and potential contamination of seafood resources and the closing of harvesting activities affect commercial and recreational fishing interests, peripheral activities that support them, and subsistence users, for whom harvested items may represent a substantial portion of the diet. The loss of revenue resulting from harvest closures and/or the loss of seafood markets carry with them widespread implications for economic, social, and possibly cultural disruption, as well as litigation for recovery of damages.

The extent to which an organism may be contaminated results from the combination of several factors, including the product to which seafood resources are exposed, the route of exposure, the metabolic detoxification systems present in organisms of interest, and the tissues eaten by the human consumer.

Nature of the product

As noted in the oil chemistry sections of this course, the crude oil and partially refined petroleum products can be very complex mixtures of hydrocarbons that vary from region to region (and within regions, as well). Focusing on the aromatic hydrocarbons as a group, it is of some importance to note that while they are considered to be hydrophobic, aromatics possess a wide range of solubilities. The degree to which a given constituent of interest is soluble in water not only determines how and how much an organism might be exposed, but also is a major factor in how the compound behaves in a biological system.

The nature of the product also is of importance from another perspective. Davis et al. (1984) noted that higher molecular weight constituents of petroleum hydrocarbons can be relatively low in acute toxicity, but may have a high potential for causing tumors or cancers:

> These high molecular weight (four- and five-ring) compounds need careful consideration since potential exists for food web transfer from fisheries to consumer, which implies a potential change from resource impact to human health risk.

Route of exposure

There are three principal ways in which hydrocarbons may interact with an organism to become contaminated (Connell and Miller 1981):

1. Ingestion of food contaminated with product.

2. Absorption of dissolved hydrocarbons through respiration, i.e., through gill tissues.

3. Absorption of dissolved hydrocarbons from the water through the skin.

The route of exposure can be influenced by a number of related and unrelated parameters, including feeding strategy, fat content of the organism, the solubility of the product(s), physical characteristics of the water mass, reproductive state of the organism, etc.

A related factor that is also important is the length of exposure. Obviously, this will affect not only potential tissue contamination of the organism, but also whether the animal experiences any direct acute or chronic toxicity.

Metabolic detoxification systems

To varying degrees, all organisms are capable of metabolizing foreign compounds in order to render them more easily excretable. The presence or absence of enzyme systems capable of processing specific materials in large part determines the ease with which hydrocarbons are processed and passed from an organism.

Some invertebrates such as bivalves do not carry the biochemical machinery necessary to metabolize petroleum hydrocarbons. As a consequence, aromatic hydrocarbons are not readily excreted and instead tend to accumulate in body tissues. It is for this reason that bivalves such as mussels, clams, and oysters are often used as "sentinel" organisms to assess environmental exposure to contaminants.

The fact that these organisms can concentrate hydrocarbons from the environment is of concern from a seafood perspective. Although shellfish may not be able to rapidly metabolize aromatic hydrocarbons, human consumers are generally able to do so owing to the presence of efficient enzyme systems. However, the by-products resulting from metabolism of some aromatic compounds can be highly reactive and are known to induce cancers or other toxicological effects.

In contrast to bivalves, fish are considered to be rapid metabolizers of aromatic hydrocarbons. This is thought to be attributable to the presence of certain enzyme systems (e.g., cytochrome P-450-dependent mixed function oxidase, epoxide hydrolase; glutathione-S-transferase) that facilitate the removal of the hydrocarbons and metabolites from their bodies. As a result, fish will generally not accumulate aromatic hydrocarbons in their flesh. In the subsequent discussion of subsistence seafood concerns, other approaches to evaluating fish exposure to hydrocarbons are described.

Tissues eaten by human consumers

Although it is somewhat obvious that specific portions of a seafood organism are favored for human consumption, ethnic and cultural differences in consumption patterns must be considered. For example, although contamination of muscle tissue of fish would be addressed as a problem in most spill situations, the fact that representatives of certain ethnic groups also use other parts such as the liver, reproductive organs, or head may necessitate a more conservative approach.

The higher lipid, or fat, content of viscera relative to muscle tissue may increase the extent of exposure to lipophilic ("fat-loving") compounds such as aromatic hydrocarbons. However, this appears to be less of a concern with respect to petroleum-related hydrocarbons than it is for such persistent organic compounds as the chlorinated pesticides or polychlorinated biphenyl mixtures, primarily because for many animals, aromatics are metabolized and removed from tissues more readily than other hydrocarbons.

Tainting

Tainting has been variously defined, but generally is considered to be the development of flavors or odors in seafood that are not typical of the seafood itself. Although causes for tainting are not necessarily limited to exposure to hydrocarbons—spoilage, for example, can cause a familiar "off" smell or taste—in the context of this discussion, the term will refer to that arising from petroleum hydrocarbons.

It should be noted that by definition, tainting comprises those examples of seafood contamination that are identifiable through normal human sensory systems such as taste or smell. Tainting, therefore, is determined by *organoleptic* analysis--which is a multisyllabic way of saying the detection of oil through taste or smell. The lighter fractions of a petroleum hydrocarbon mixture are those that would be most likely to be detected through organoleptic sampling; the heavier weight aromatic hydrocarbons, many of which have been identified as having carcinogenic implications, would remain undetected through smell or taste analyses. An additional implication of this is that organoleptic tests would be of greatest use early in a spill event, before weathering reduces the more volatile components.

Because it is a sensory phenomenon, tainting is difficult to quantify. It is dependent on both the sensitivity as well as the preference of the individual, both of which obviously can be quite variable. Perception, too, enters into the determination of tainting. Tidmarsh and Ackman (1986), in an excellent review discussion on the subject, note:

> Fear of tainting can be as serious a problem as an actual tainting incident. Consumer resistance, closures imposed by regulatory authorities, and embargoes on harvesting activities by producers resulting from even the remote possibility that seafoods are tainted can cause severe economic losses.

In an oil spill situation, real or perceived tainting will result in a tremendous amount of public and business interest concern, and inevitably, political posturing. There are likely to be pressures to improve the measurement of the extent of contamination, which will lead to chemical analyses.

Chemical analysis

Organoleptic methods of seafood testing are not only limited as to the chemical compounds that can be detected (e.g., low vs. high molecular-weight aromatic hydrocarbons), but also are limited by a "detection limit," below which even a sensitive evaluater cannot smell or taste evidence of tainting. An approximate lower limit for organoleptic detection of emulsifiable oil is 15 ppm, although certain crude oil constituents are detectable at lower levels (e.g., kerosene at 0.1 ppm, naphthalene at 1.0 ppm, toluene at 0.25 ppm). Other references cited in Connell and Miller (1981) found that tainting is caused by levels of refined or crude petroleum products in the range of 4 to 300 ppm. These levels are generally well above established levels of concern for a number of hydrocarbon compounds.

In order to avoid the detection limitations of organoleptic methods, to eliminate the large degree of subjectivity involved, and to elicit relatively repeatable quantitative results that can serve as the basis for comparison for regional or time-series analyses, chemical methods are used. While chemical analyses require laboratory facilities and can be very expensive, they vastly improve the range of compounds measurable and the levels to which results can be quantified.

Case history

There have been many oil spills where commercial fishing concerns have arisen, impacts on fishing activities realized, and severe financial burdens imposed. During the *Amoco Cadiz* incident, for example, the oyster industry in Brittany was forced to destroy in excess of $2 million worth of seafood (Tidmarsh and Ackman 1986), while total costs to the oyster industry were estimated at nearly $26 million (Sorenson 1983). Both fish and shellfish were reported to have been tainted in the wake of the *Torrey Canyon* spill (Connell and Miller 1981). Closer to home, Blumer et al. (1970) described and studied the tainting and chemical contamination of edible shellfish following a spill of No. 2 fuel oil in Buzzards Bay, Massachusetts.

Much less common are spills where subsistence seafood concerns become an issue, and in most state waters, these would not be expected to be as significant as they were in Alaska, or in the recent *Tenyo Maru* spill off the coast of Washington state. However, subsistence harvesting is not necessarily limited to Native American peoples; certain ethnic groups, including recent immigrants from Europe or Asia, may rely heavily on subsistence seafoods. For the sake of convenience and because the example is a fairly recent one, the *Exxon Valdez* spill is used here as a case history that included both commercial fishing concerns, as well as significant subsistence seafood issues.

Exxon Valdez

Commercial fishing impacts

From the beginning of the spill in March 1989, concerns were voiced about possible contamination of commercial fishing harvests in the affected area. The implications to the seafood industry in Alaska were obvious: Prince William Sound and the Gulf of Alaska produce the largest tonnage of halibut in the U.S.; Kodiak has consistently ranked as a leading U.S. port in terms of catch landing weights as well as values; Prince William Sound alone had been expected to produce a salmon harvest worth $70 to 100 million (NOAA 1990). Other fishing-related activities contributed additional millions of dollars of activity to the state economy.

Although little hard evidence existed that oil was contaminating commercial fisheries resources, the Alaska Department of Fish and Game and the Department of Environmental Conservation reacted in two ways to allay fears about contamination of fish and shellfish:

1. Closure of commercial fisheries in the area most heavily affected by oil, where oil was evident on the water surface or on adjacent shorelines;

2. Adoption of a "zero tolerance" policy for fish catches, under which any visible tainting of commercial catches would result in closure of the affected fishery.

There was evidence that some of the oil sightings which resulted in commercial fishing closures were attributable not to the oil spill, but ironically, to leakage of refined products from fishing vessels themselves. Trajectory models and previous experience of NOAA scientists had suggested a low probability that the oil sighted was from the Exxon Valdez, and subsequent chemical analysis confirmed that this was true.

Additional efforts by the U.S. Coast Guard and NOAA provided overflight information and trajectory analyses to commercial fisherman in order that known or projected areas of contamination could be avoided during fishing activities. All of these steps were taken primarily to prevent the market perception of contamination and to maintain public confidence in the quality of Alaskan seafood.

Subsistence seafood issues

(Material for this summary was provided by L. Jay Field, NOAA, and is drawn largely from Field and Walker 1990).

The area affected by the *Exxon Valdez* spill included 18 mostly rural communities with a combined population of over 15,000 residents. Although the towns and villages included larger fishing ports such as Kodiak, Seward, and Cordova, most of the communities were small, predominantly Alaskan Native villages. Residents of the villages relied heavily on subsistence fish, shellfish, birds, and mammals to provide protein in their diets. Because of this, the oil spill had the potential to affect health and lifestyles in a fundamental way, and levels of concern in the villages were understandably high.

One of the first responses to subsistence concerns was the formation of the Alaska Oil Spill Health Task Force (OSHTF), an interagency group chaired by an Indian Health Service physician with representatives from state and federal agencies, native organizations, and Exxon. The task force served as the focal point for discussion and for activities to assess the extent of seafood contamination.

Meanwhile, in May and July of 1989, the state of Alaska epidemiologist released bulletins discussing health implications of the spill, and advising residents to use organoleptic means for determining the safety of harvested seafoods: i.e., if the seafood did not appear to be contaminated by visual observation, smell, or taste, it was probably safe to eat.

Concerns of villagers remained high. In early summer of 1989, Exxon began planning a study to analyze large numbers of subsistence fish and shellfish for aromatic hydrocarbon contamination. At the same time, the U.S. Coast Guard and the OSHTF requested that NOAA take an active role in addressing subsistence seafood concerns of Native villagers. A result of these events was an agreement between Exxon and NOAA to cooperatively study the potential contamination of subsistence seafoods collected in areas traditionally fished by communities. NOAA and Exxon biologists would make the field collections in consultation with representatives from the various villages, with chemical analyses performed by the National Marine Fisheries Service Environmental Conservation Division laboratory in Seattle. The OSHTF reviewed the study objectives and was instrumental in determining means of communication of goals and results to affected villages.

Collections of shellfish, bottomfish, and salmon were made in approximately 13 subsistence areas, with control samples also collected in unoiled regions. Edible tissues from fish and shellfish were analyzed for aromatic hydrocarbon contaminants, selected to reflect the constituents found in Prudhoe Bay crude oil and to include those that were considered to be persistent in the environment with implications for long-term human health impacts. Bile from fish was also collected, as fish rapidly metabolize aromatic hydrocarbons and the by-products are concentrated in bile prior to excretion. Bile analyses were used as a rapid screening test for indications of exposure to hydrocarbons.

In 1989, when levels of exposure to the organisms would have been highest, 143 samples of shellfish (mussels, clams, chitons) and 210 samples of fish (three species of salmon, and halibut) were analyzed. Shellfish from two areas showed relatively high levels (>1000 ppb) of total aromatic hydrocarbons. One area was Windy Bay, a site on the Kenai Peninsula which had been heavily oiled. The other was Near Island, which is adjacent to the boat harbor in Kodiak. Two other areas (Chenega and Old Harbor) yielded shellfish with levels >100 ppb, while samples from the remainder of the sites were generally <10 ppb and comparable to uncontaminated control samples.

The high concentrations of hydrocarbons in Windy Bay samples were clearly associated with the *Exxon Valdez* spill. Those from Near Island, however, were much more questionable in origin, as they were found in an area not known to have been directly impacted by the spill. Moreover, the collection site was adjacent to a busy boat harbor, where small spills of fuel and other petroleum products are common. Examination of the ratios between lower-weight aromatic hydrocarbons and higher-weight aromatic hydrocarbons supported the idea that hydrocarbons contaminating the shellfish near Kodiak were not of *Exxon Valdez* origin. Similarly, samples from the Chenega site, which showed moderately elevated hydrocarbon levels, were collected in an area with many derelict wooden pilings that had been treated with creosote, and an area that had also experienced an unrelated fuel oil spill in the recent past.

Generally speaking, tissue hydrocarbon levels in finfish were about an order of magnitude less than those found in shellfish. Although bile analysis in salmon indicated some exposure to hydrocarbons, of the 210 samples of edible fish tissue analyzed in 1989, only 11 samples exceeded 10 ppb total aromatic hydrocarbons in edible tissues, and only one exceeded 100 ppb.

The significance of the hydrocarbon levels found in the subsistence seafoods was an extremely difficult issue to address. No advisory levels or other guidelines for the safety of foods contaminated with oil were available at the time of the spill, and a review of literature showed that little information existed on the health effects of oil-contaminated seafood. To interpret the study results, NOAA convened two meetings of specialists from several disciplines related to human health implications of eating contaminated seafood. Representatives included scientists from the U.S. Food and Drug Adminstration (FDA), the National Institutes of Environmental Health Sciences, the Agency for Toxic Substances and Disease Registry, the University of Alaska, NOAA, and Exxon Biomedical Research Sciences.

The group concluded that finfish from all areas were safe to consume, but that shellfish from areas that contained the relatively highest concentrations (i.e., Windy Bay and Near Island) should be avoided. These recommendations were included in newsletters sent to all villages, and OSHTF representatives visited each affected community to present and explain the findings, and to answer questions.

A direct request from the OSHTF to the FDA to perform a risk analysis based on the analytical chemistry results and the known patterns of subsistence seafood consumption resulted in the issuance of a highly qualified opinion that the additional cancer risk imposed by consumption of oil contaminated subsistence seafoods—even the most heavily contaminated shellfish from Windy Bay and Near Island—was low.

The success of the risk communication efforts to the villages was mixed. The chemistry data and interpretation of results were not successful in allaying concerns about subsistence seafood safety. As Field and Walker noted:

> The high degree of alarm experienced by the village communities about subsistence food safety made them unreceptive to reassurances based on qualitative measures such as organoleptic testing. In addition, their apprehensions were reinforced by the long interval between the collection of tissue samples for analysis and the communication of interpreted results. A risk communication workshop. . .with representatives from six villages revealed differences between individuals in the effectiveness of the conclusions about food safety. The consensus, however, was that communications efforts need to begin immediately following a spill and continue at frequent intervals, and that those affected should be directly involved in the process. A variety of approaches should be used that include a mix of written and face-to-face communication techniques.

The *Exxon Valdez* experience illustrates many of the problems that may be unavoidable even with well-planned and well-funded efforts to address concerns about contaminated seafoods, both from commercial fishing and subsistence user perspectives. The suspicion and tendency to disregard analytical results from analysis of potentially contaminated seafood that was evident with Native communities in Alaska may to some extent reflect reactions that could be expected from the public at large in the event of an oil spill occurring in an area with important fisheries resources. Noting the critical nature of *perception* in dealing with sensitive markets, the concept of highly visible efforts to prevent potentially contaminated seafood from reaching the market is worth considering, even if the chances for contamination is realistically considered to be low.

In a summary of the *Exxon Valdez* experience, Walker and Field (1991) observed that initial oil spill response activities have generally assigned a lesser priority to human health concerns that might arise from contamination of seafood. This was attributed to the low probability that fish would be exposed to high levels of hydrocarbons, the ability of fish to relatively rapidly metabolize petroleum-related compounds, and the ability of human consumers to detect tainted seafood through smell and taste. Because the risk to human health has been considered to be low, the National Contingency Plan does not provide guidance to planners and responders. As a result, fisheries and human health issues are not raised explicitly until fishermen, fisheries agencies, or the public do so. Because of the potential for substantial impacts attributable to seafood concerns, planners and responders would be well-advised to anticipate these considerations and incorporate them into regional or local contingency plans.

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5 Oil Spill Response and Cleanup Techniques

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Chapter 5.
Oil Spill Response and Cleanup Techniques

Introduction

The majority of oil spills (number of events) occur in coastal waters or in ports. Therefore, contamination of the shoreline is likely at most spills, and thus the issues of oil recovery and shoreline cleanup must be addressed. Nearly all shoreline cleanup methods have some kind of environmental impact, so selection of a cleanup method inherently forces us to make some kind of tradeoff of the effects of the oil versus the effects of the cleanup. In this chapter, we describe some of the commonly used techniques for oil spill response and shoreline cleanup. There has been little innovation in the physical removal technologies since the 1970s. The only really new techniques developed in the last few years involve chemical and biological treatment methods.

Open Water Response Techniques: Dispersants

It has been nearly 25 years since the *Torrey Canyon* oil spill, where large amounts of highly toxic degreasers were applied directly to oiled rocky shores, marshes, and sand beaches in England. The impacts to intertidal biological communities were extensive and well documented (Smith, 1968). This very negative experience led to the prohibition of dispersant use in many countries and the perception that all dispersants are highly toxic. Since that time, there has been much talk and little "action" about dispersants. New formulations have been produced, many of which have acute toxicities lower than the constituents and fractions of most crude oil products (NRC, 1989). There have been extensive laboratory and field tests on effectiveness and toxicity, and workshops and protocols for dispersant-use decision making during spills. The number of papers presented at the Oil Spill Conference over the last ten years reflects the growing interest in the potential for use of dispersants in the first half of the decade and the dropoff in interest in the second half as dispersants failed to become an accepted spill response tool:

1981	-	15 papers in two sessions
1983	-	10 papers scattered around in various sessions
1985	-	25 papers
1987	-	30 papers
1989	-	15 papers
1991	-	11 papers

There are many good reports on dispersants, including the most recent (1989) National Research Council publication *Using Oil Spill Dispersants on the Sea*. In this section we only briefly summarize the key issues on dispersant application, test results, toxicity, and guidelines for decision making on dispersant use.

Dispersant Types and Application Methods

Simply stated, dispersants work because they contain surfactants–chemicals which have molecules that have a water-compatible end and an oil-compatible end. At the proper concentration and mixing energy, the surfactant molecules can attach to oil particles and reduce the interfacial tension between oil and water. This reduction in the oil-water interfacial tension allows oil droplets to break off from the slick and minimizes the tendency to re-coalesce (Fig. 5-1).

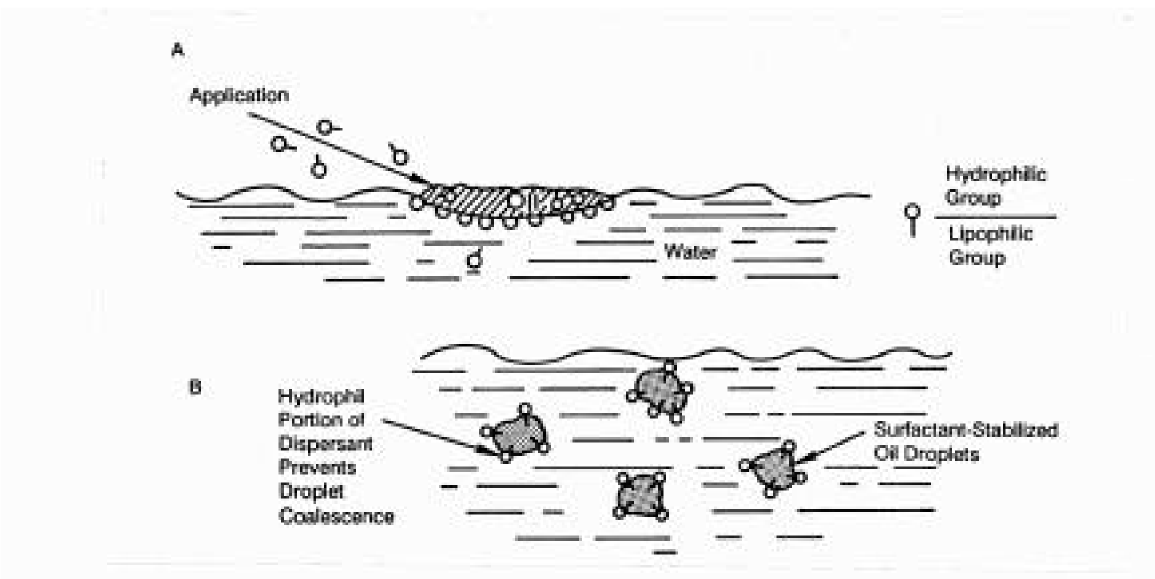

Figure 5-1. Mechanism of chemical dispersion. A) Surfacant locates at oil-water interface. B) Oil slick is dispersed into micelles or surfactant-stabilized droplets. (Canevari, 1969.)

Although the detailed composition of dispersants is proprietary, their general characteristics are broadly known. The most commonly used surfactants are nonionic formulations, such as sorbitan monooleate, ethoxylated sorbitan monooleate, and polyethylene glycol esters of unsaturated fatty acids. Modern formulations contain:

- 15-75 percent of one or more nonionic surfactants
- 5-25 percent anionic surfactant
- Solvent of either:
  -water
  -water-miscible hydroxy compounds
  -hydrocarbons

Dispersants are applied either "neat" or diluted. The standard dosage is a dispersant:oil ratio of 1:20. Assuming an average slick thickness of 0.1 mm, this dosage would require five gallons per acre of dispersant. However, it should be noted that nonuniformity of the slick is a very real problem in dispersant applications. In the U.S., the effort has been to have a range of aircraft available for spraying dispersants on short notice, and there has been considerable research on optimization of droplet size and the equipment needed to produce the droplets.

NRC (1989) lists four criteria for effective dispersal of oil:

1) **The dispersant must reach the slick**, which can be a major problem if strong winds blow the droplets away from the slick, or visibility limits the ability to accurately position the aircraft over the slick during application.

2) **The dispersant must mix with the oil or move to the oil-water interface.** This is where droplet size becomes important; too large droplets pass right through the slick and too small droplets stay on the oil surface or blow away.

3) **The dispersant must reach the proper concentration at the interface**, so that a maximum reduction in the interfacial tension is reached. Note that dosage is never uniform or well-known because of nonuniformity in the slick thickness.

4) **The oil must disperse into droplets**. Therefore, some minimum energy is needed for dispersants to work.

These logistical factors are obviously difficult to overcome. An added problem is that dispersant efficiency testing shows that many dispersants are not very effective, even under controlled laboratory conditions. Fingas et al. (1991a) used the "swirling flask" test to measure the effectiveness of four dispersants on a range of crude oils (with emphasis on those important to Canada). Table 5-1 lists the test results. It is obvious that there are clear differences among dispersants and oils. The average effectiveness was as follows:

Table 5-1. Dispersant effectiveness and oil properties. (Fingas et al., 1991a.)

Oil	Dispersant effectiveness (in percent)			Hydrocarbon analyses (weight percent of total)			Asphaltenes (weight percent)	Waxes (weight percent)	Viscosity (cs)
	Corexit	Enersperse	Dasic	Saturates	Aromatics	Polars			
Adgo	61	59	8	79.8	18.8	0.9	0.59	0.88	66
Amauligak	45	62	28	89.5	9.3	0.4	0.31	0.87	16
Arabian Light	17	22	33				2.61	1.76	
ASMB	33	51	24	84.2	12.8	1.2	1.55	1.74	16
Atkinson	39	73	49				2.39	0.72	57
Avalon J-34	11	11	16	83.2	12.5	1.8	2.48	3.22	14
Bent Horn	17	23	35	94.3	4.8	0.3	0.4	2.11	24
Bunker C	1	1	2	20	35	15	6.73	1.23	48,000
California API = 11	1	1	1	13.7	29.8	31.4	18.63	2.37	34,000
California API = 15	1	1	1	13.7	36.4	24.1	20.13	1.6	6,400
Cohasset A-52	95			90	2		0.35	0.9	2
Cold Lake Heavy	2	1	1	16.6	39.2	19.3	11.87	1.35	235,000
Endicott	7	6	14				3.16	0.54	92
Federated	25	40	38	87.1	10.9	1.3	0.9	1.96	4.5
Hibernia	6	10	14	82.1	13.5	2	3.62	1.1	92
Issungnak	66	60	51	91.5	2.7	0.3	0.53	1.2	4
Lago Medio	5	13	15				4.53	1.43	47
Norman Wells	36	51	26	85.1	11.1	1.6	1.15	1.25	6
Panuke F-99	96	96	40	90	2		0.29	0.83	1.5
Prudhoe Bay	7	10	14	78.3	17.6	2.5	2.04	0.65	35
South Louisiana	31	48	42	65.1	26.3	8.4	0.2	1.06	
Syncrude	63	61	25	81.8	17	0.9	0.2	1.42	5
Terra Nova	16	28	40				0.59	0.89	26
Transmountain	20	28	27	81	13.6	1.9	3.23	1.39	12

- Heavy crude oils — 1 percent
- Medium crude oils — 10 percent
- Light crude oils — 30 percent
- Very light crude oils — 90 percent
- Weathered oils — Always lower than fresh

Weathering is an important factor in the decision to attempt use of dispersants. Most researchers have shown that dispersant effectiveness is closely tied to viscosity: dispersants are most effective at viscosities below 2000 centistokes (cSt) and not effective at all above 10000 cSt (Cormack et al., 1986/87). Figure 5-2 shows the increase of viscosity for selected crudes over time, indicating the point after which dispersant effectiveness would drop significantly. This information and others has led to the rule of thumb that dispersants must be applied within the first 24 hours to be effective.

A recent paper by Fingas et al. (1991b) summarizes laboratory studies on dispersant effectiveness correlated to temperature, salinity, dispersant dosage, and the percent composition of asphaltenes, aromatics, polar compounds, saturate compounds, and waxes. Figures 5-3 through 5-7 shows the results using Alberta Sweet Mixed Blend

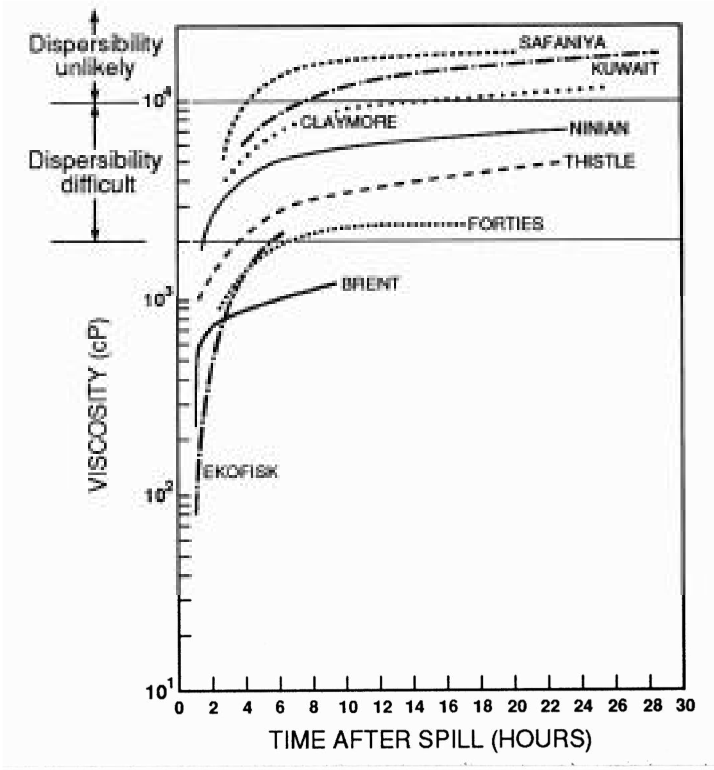

Figure 5-2. Increase of viscosity of several crude oils with weathering. (Cormack et al., 1986/87.)

and Corexit 9527, except where noted. Fingas et al. (1991b) summarized their studies as follows:

- Effectiveness increases exponentially with temperature.
- Optimal salinity is 40 parts per thousand, with rapid decreases on either side. Dispersants formulated for marine application are not effective at all in freshwater.
- Dosage is very important.
- Effectiveness is positively correlated with saturate content.
- Effectiveness is negatively correlated with the asphaltene, aromatic, and polar content.
- Effectiveness is not directly related to viscosity, but rather to the asphaltene content, which strongly correlates with viscosity.

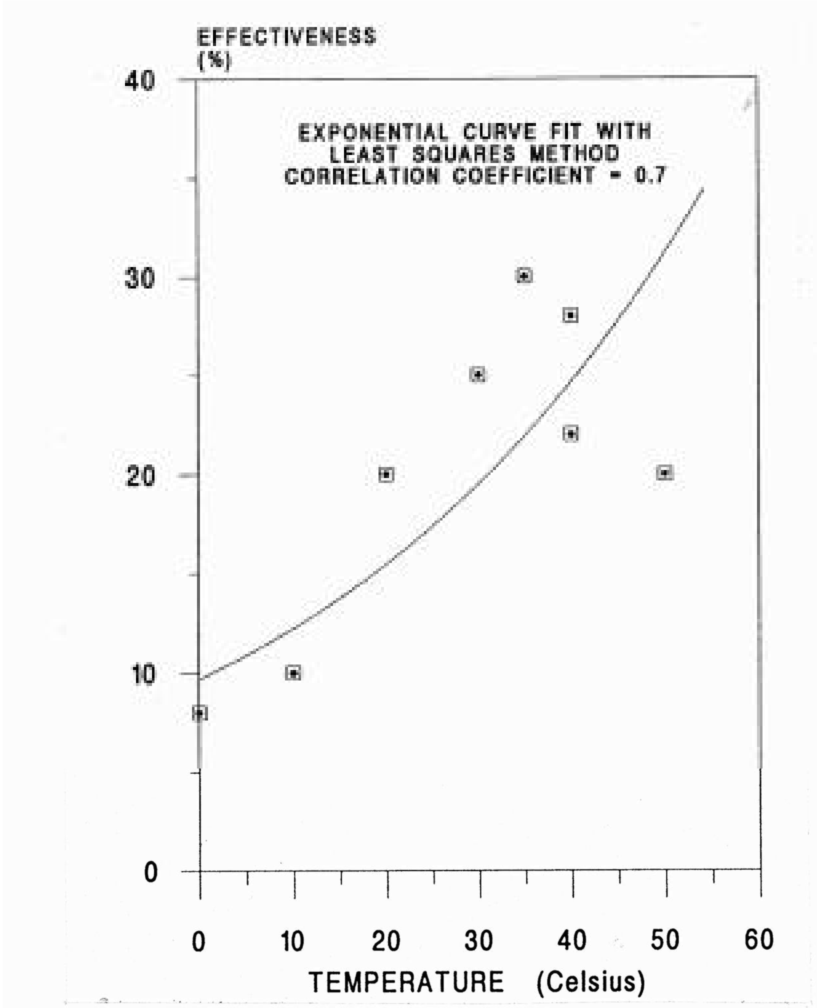

Figure 5-3. Variation of dispersant effectiveness with temperature. (Fingas et al., 1991a.)

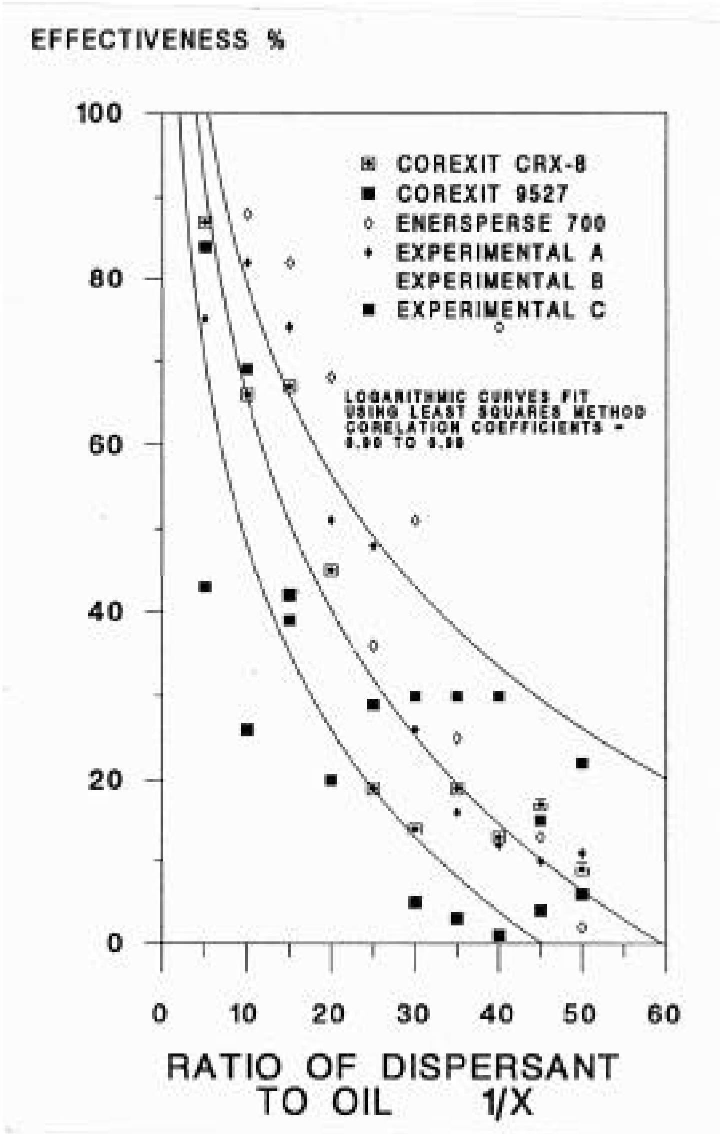

Figure 5-4. Variation of dispersant effectiveness with dispersant quantity. (Fingas et al., 1991a.)

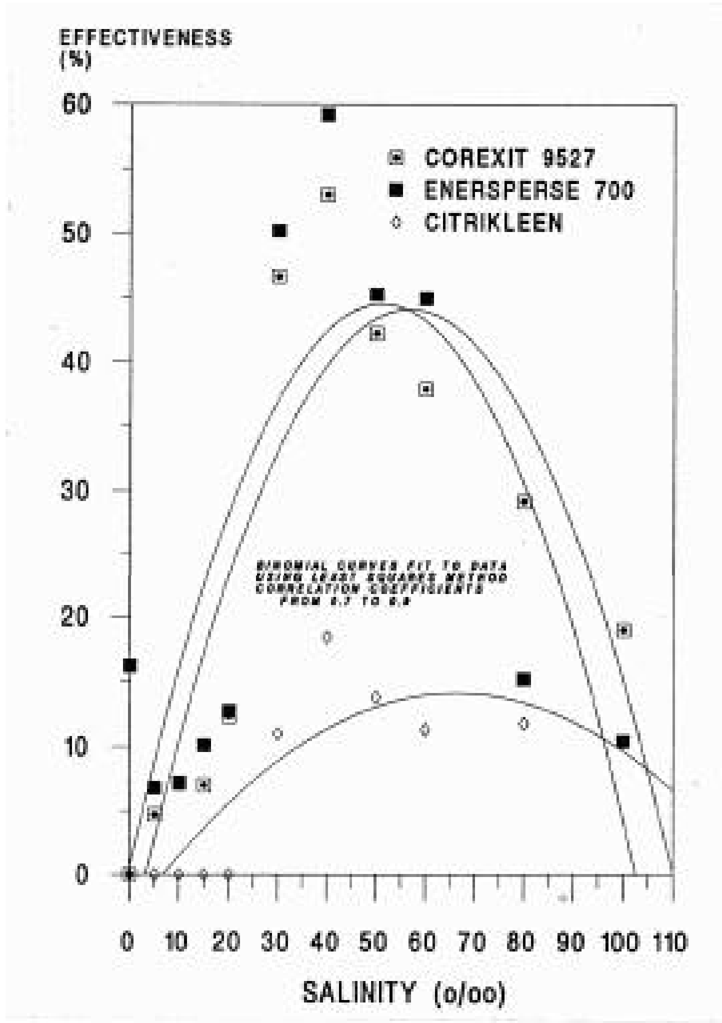

Figure 5-5. Variation of dispersant effectiveness with salinity. (Fingas et al., 1991a.)

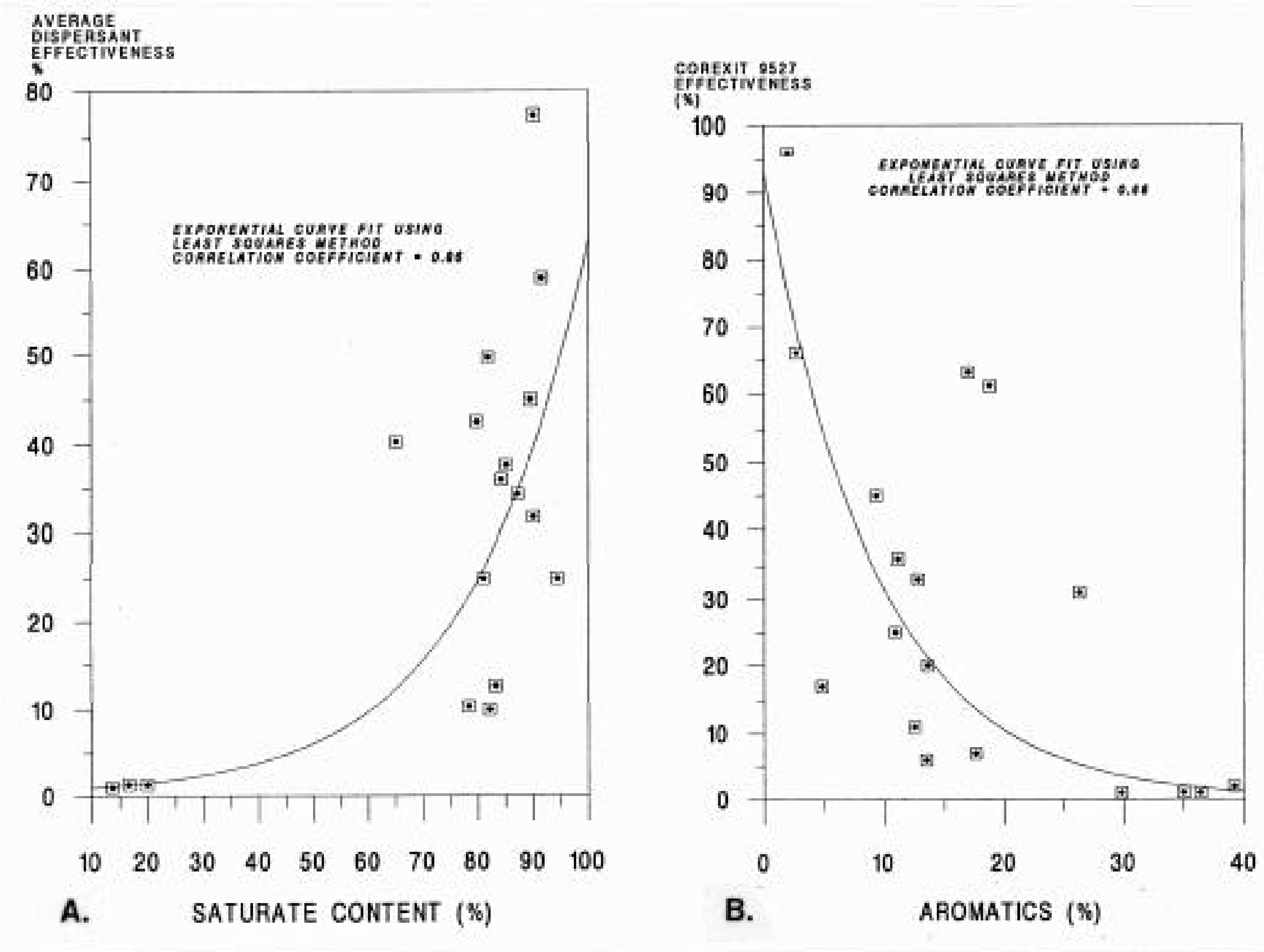

Figure 5-6. Correlation of dispersant effectiveness with A) saturate content, and B) aromatic content. (Fingas et al., 1991a.)

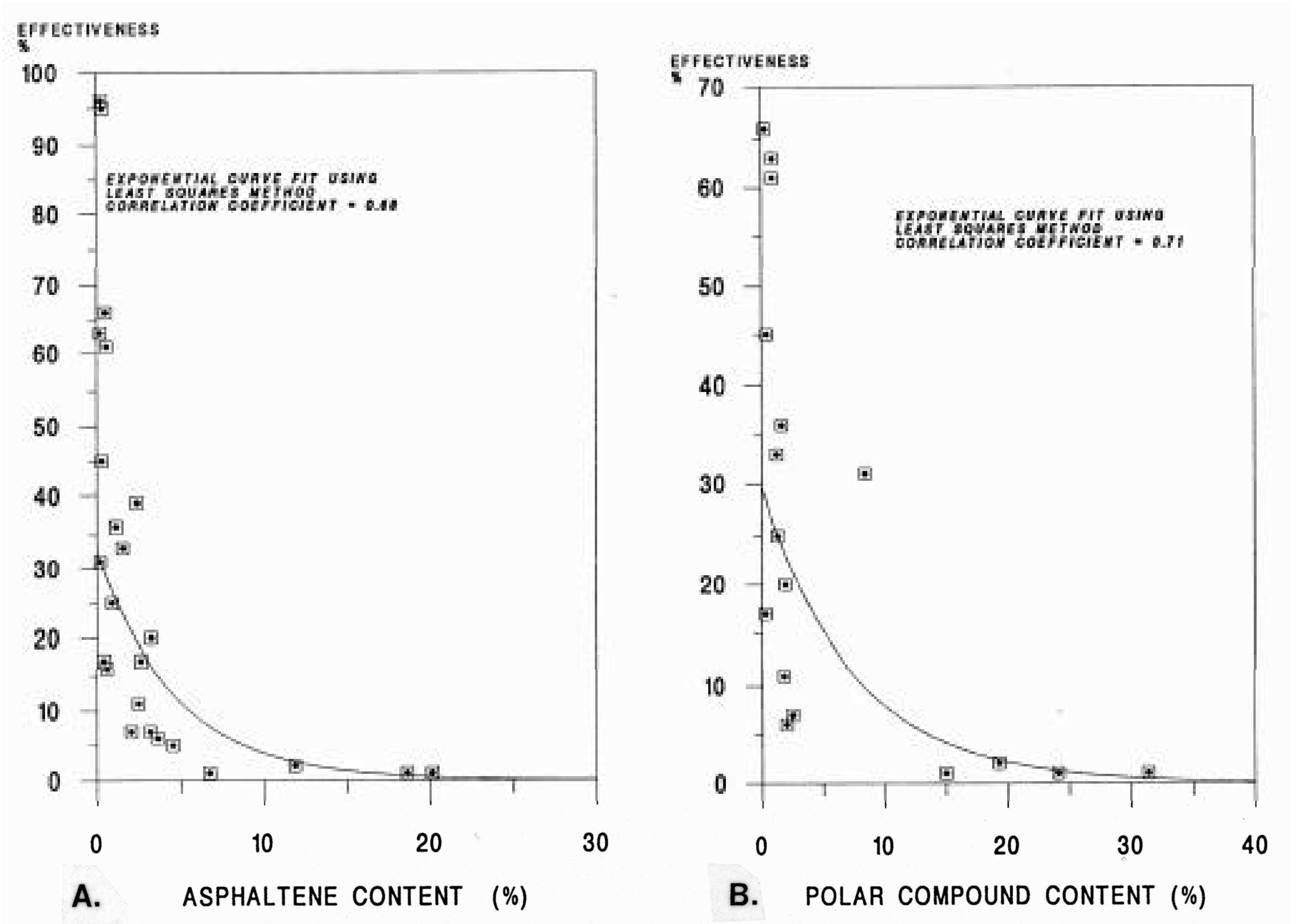

Figure 5-7. Correlation of dispersant effectiveness with A) asphaltene content, and B) polar compounds content. (Fingas et al., 1991a.)

Review of Dispersant Tests

Field test results have been highly varied. Fingas et al. (1991a) report that there have been 107 test spills for determining dispersant effectiveness in the last 12 years. Results were reported as an estimate of the effectiveness percentage for only 25 spills. The average effectiveness was 30 percent, with values ranging from 0 to 100 percent. Most of the time, effectiveness was determined by measurement of the concentrations of oil in the water column below dispersed slicks. Surface slick dimensions were used to calculate the amount of dispersed oil. Fingas et al. (1991a) argues that this approach is invalid because surface slicks have little positional relationship to the underwater dispersed plume.

Open-ocean field trials are the best indication of dispersant effectiveness and the likely concentrations of oil in the water column over time and with depth. Water-column concentrations are particularly important in the assessment of impacts to organisms. The best-documented field trials in the U.S. were sponsored by API, at locations off New Jersey in 1978 and California in 1979, reported in McAuliffe et al. (1981). Figure 5-9 shows the California test results for Prudhoe Bay crude oil sprayed with Corexit 9527 from aircraft immediately after release. Within 30 minutes, the highest concentrations of dispersed oil in the water column averaged 41 ppm at 1 meter and 10 ppm at 3 m (Fig. 5-7a). Nearly 40 percent of the oil was dispersed into the top 2 m. After one hour, downward mixing of the dispersed plume was evident (Fig. 5-7b), with 31 percent of the oil in the top 2 m, 24 percent at 2-4 m, and 29 percent at 4-7.5 m. After three hours, maximum concentrations of 1-2 ppm were recorded through 6 m and 0.5 ppm at 9 m. Other field trials in the North Sea, Canada, and France have shown similar results (summarized in NRC, 1989, Table 4-3), with maximum concentrations of 1 to 100 ppm in the top meter.

These field results are are not very different than the model calculations of Mackay and Wells (1983), which predict a maximum concentration of 1 ppm at 10 m depth (Fig. 5-8). The general rule that dispersants should not be used in water depths less than 10 m is derived from the assumption that 1 ppm is a threshold for acute toxicity above which impacts to benthic organisms might occur.

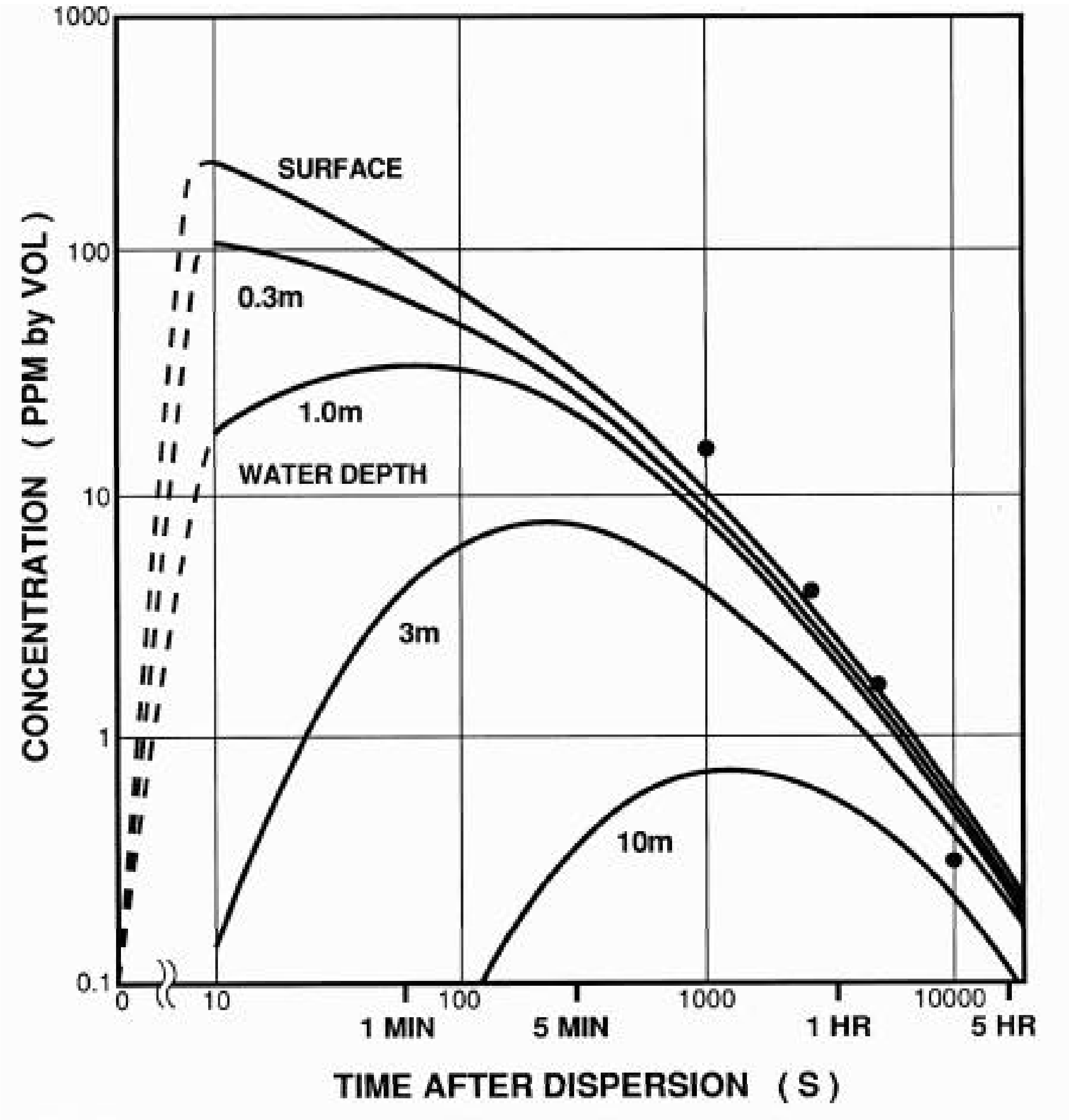

Figure 5-8. Predicted concentrations of dispersed oil under a slick 0.15 mm thick for selected periods after dispersant application. The dots are the actual values from the California sea trials in McAuliffe et al. (1981).

Monitoring of Dispersant Applications

There have been very few spills in the U.S. where approval was granted for use of dispersants in combatting the spill. Typical of emergency conditions was the spill associated with the fire and breakup of the *Puerto Rican* in 1984 off the Farallon Islands. Nearly 2,000 gallons of Corexit 9527 were applied to the slicks three days after the initial incident. Weather prevented implementation of the water-column monitoring program originally required, thus effectiveness was measured by visual observation. But, observers were not able to reach consensus on how much oil was dispersed, though most estimates ranged from 0 to 30 percent.

It is obvious that we will never resolve the issue of whether dispersants work and what are the impacts to water-column organisms compared to undispersed slicks without high-quality field monitoring plans. But, how are we to be prepared for such a monitoring program under emergency conditions when quick approval to proceed is being sought to optimize effectiveness? The only solution is having a detailed, yet flexible plan, trained people, and a lot of luck. NOAA has been involved in two "spills of opportunity" where they tested various dispersant monitoring strategies: the *Pac Baroness* off California in 1987 and the *Mega Borg* off Galveston, Texas in 1990. These monitoring results are summarized in Payne et al. (1991a; b). Lessons learned from these two spills include:

- There must be **good** communications among the various aircraft and boats involved in direction, observation, and sampling.
- A very detailed plan must be developed, in advance, with the roles and responsibilities of each group spelled out.
- Both videotape and 35 mm photography should be used for documentation. The video camera should be mounted on the nose of the observation helicopter and a remote used to direct it. Whenever possible, a surface vessel or other feature should be kept in the field of view for reference and scale.
- If water-column sampling is required, continuous flow fluorometers are useful but samples are needed for confirmation of dispersed oil concentrations.
- For large applications, SLAR and IR/UV remote sensing are good techniques for monitoring the slicks.

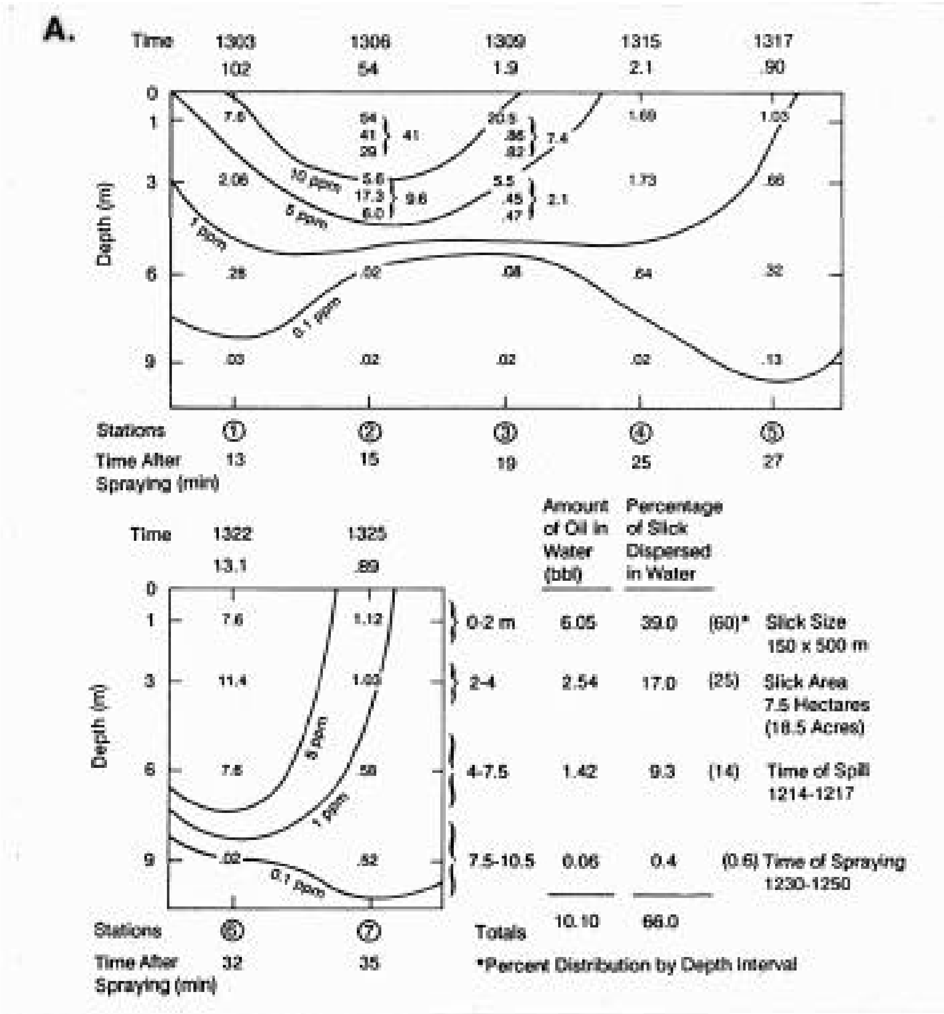

Figure 5-9. Results of water sampling at the California 1979 dispersed oil experiments, where 20 barrels of crude oil were treated (McAuliffe et al., 1981). A) Immediately after the application of dispersants, maximum concentrations in the top meter averaged 41 ppm.

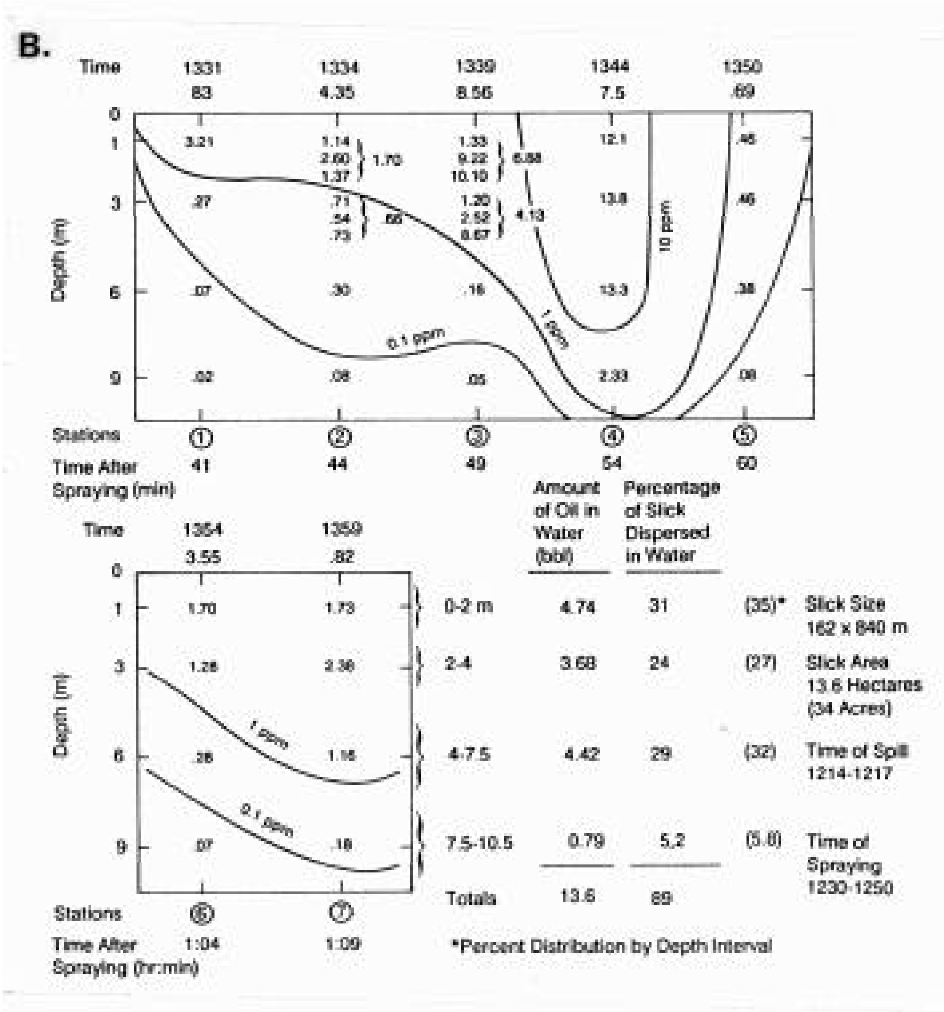

Figure 5-9. Continued. B) Concentration of oil (in ppm) in the first hour after dispersant application.

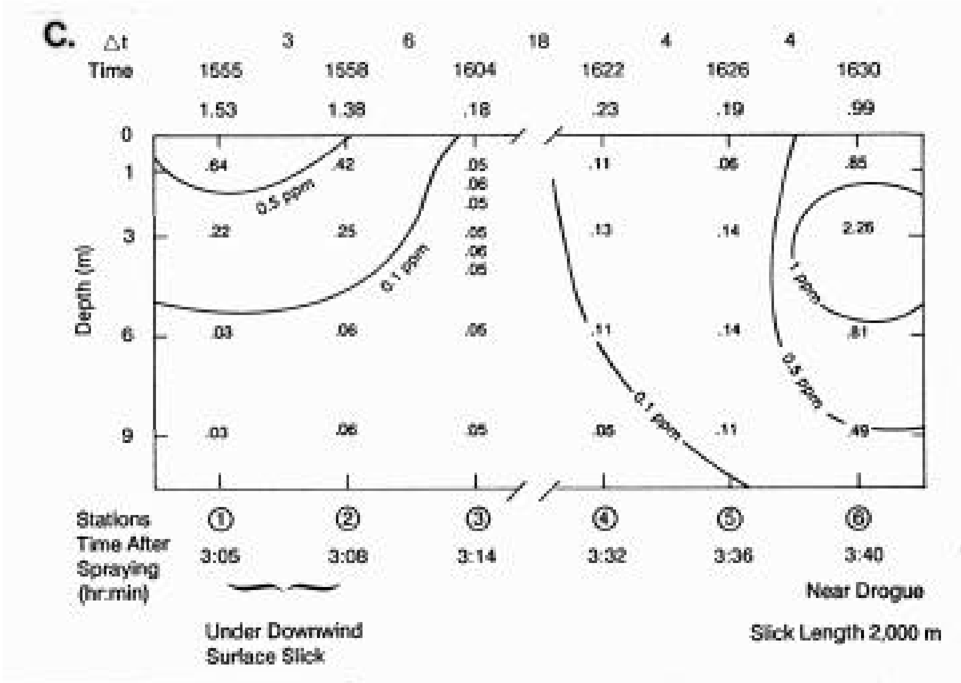

Figure 5-9. Continued. C) Concentration of oil (in ppm) 3-4 hours after dispersant application. Note that the highest concentrations were near the drogue, at about 2 ppm.

Many groups question whether a monitoring program can, in reality, include a water-column sampling component. Only under the best of conditions is it likely that a comprehensive and well-conducted water sampling program will be possible. In the two recent spill of opportunity dispersant monitoring programs, the spills were on-going, with a continual release of fresh oil. In the NOAA studies, the monitoring groups had 1-3 days to prepare, and the results were still less than optimal. Anyone can imagine what it would be like to get a water sampling program off "at first light" after finally getting approval to use dispersants that evening! It might be better to concentrate on training and logistics for high-quality visual and photographic observations.

Toxicity of oil spill dispersants

Introduction

In 1967, the tanker *Torrey Canyon* spilled nearly 1 million bbl of crude oil into the waters off the coast of England. In the two weeks that followed, approximately 10,000 bbl of chemical dispersants were sprayed on the impacted waters and shoreline in an attempt to remove the spilled oil. The biological results of this application bordered on the disastrous, and were highly visible. On rocky shorelines, mortality to intertidal organisms was clearly evident; molluscs such as limpets, snails, barnacles, and mussels were particularly hard hit. Subsequent toxicity evaluations of the most widely used product showed that the concentration necessary to kill half of populations of subtidal test organisms in 24 hours (LC_{50}) ranged between 0.5 to 5.0 ppm. LC_{50} values for intertidal organisms ranged between 5.0 ppm and 100 ppm. The concentrations at which the dispersants were toxic to all organisms were much lower than the concentrations required to disperse the stranded oil (1:2-4, dispersant:oil), and very much lower than actual application amounts (10,000 tons of dispersants to 14,000 tons of stranded oil) (Southward and Southward 1978).

In this instance, ecological impact clearly took a back seat to the mandate to remove the spilled product. Priorities were esthetic, not ecological (National Research Council 1989). However, the consequences of this treatment philosophy were long-term, and Southward and Southward noted that ten years after the *Torrey Canyon* incident, heavily oiled locations that had received repeated applications of the dispersants had apparently not recovered to a state comparable to lightly oiled, lightly dispersed areas.

The National Research Council (1989), in recounting the sequence of events, noted:

> . . .adverse publicity during and after the *Torrey Canyon* incident gave dispersants a bad reputation. Indeed, the experience led to a very cautious attitude toward dispersant use among several industrialized nations.

In the 25 years since the *Torrey Canyon*, a number of changes have taken place to improve the perceptions about dispersants. Nevertheless, dispersant use as a spill response technique has been employed relatively sparingly, with mostly inconclusive results, in the intervening years. The National Research Council cited only only six examples in which dispersants were used operationally in spill response between the *Torrey Canyon* incident and 1989. The *Exxon Valdez* in 1989,*Mega Borg* in 1990, and the*Vesta Bella* barge sinking in the Caribbean in 1991 involved the use of dispersants, also with mixed results.

The most significant change affecting the acceptability of dispersant use is associated with the dispersants themselves: older dispersant formulations were essentially industrial degreasing agents, identical or similar to those used for cleaning engine rooms and bilges. These contained a number of toxic hydrocarbon-based constituents, such as kerosene, mineral spirits, and naphtha. So-called "second generation" oil dispersants have much different formulations, with less toxic ingredients such as alcohols, glycols, and glycol ethers (Fingas et al. 1979). One of the most common and widely stockpiled of the newer dispersants is Corexit 9527, manufactured by Exxon. It is a mixture of non-ionic (48%) and anionic (35%) surfactants in a hydrocarbon solvent (17%). The surfactant formulation includes ethoxylated sorbitan mono- and trioleates, sorbitan monooleate and sodium dioctyl sulfosuccinate. Solvents in Corexit 9527 are ethylene glycol monobutyl ether and water (Singer et al. 1990).

Acute toxicity of newer dispersants appears to be considerably less than the older, Torrey Canyon-zera products; Fingas et al. (1979) noted about a 30-fold difference in 96 hr. tests with rainbow trout. The National Research Council, in its recent review, concluded that toxic effects of dispersants are generally less than crude oils and refined products. However, exposure to second generation dispersants has also been demonstrated to result in adverse effects on marine organisms, and it is important to factor toxicological implications of dispersant use into the decision matrix for oil spill response.

General dispersant toxicity considerations

The explicit consideration of toxicological effects resulting from dispersant use is not a straightforward task. It can, in fact, be quite confusing and confounding to the decision-making process. The bottom line of toxicity to an ecosystem or a specific living resource in question is very much a function of at least five components: the dispersant, the oil being dispersed, the nature of exposure (i.e., concentration and length), the organism in question, and the life stage of the organism in question. The combination of these factors, as well as others that may be relevant in specific situations, will determine the ultimate impact on the resources.

Beyond consideration of the toxicity of dispersants alone, the toxicity of dispersed oil that would be expected to result from an application also should be factored into the ecological assessment. The National Research Council concluded that acute toxicity of dispersed oil was generally attributable to the oil fraction rather than the dispersant fraction. Assuming that dispersed and untreated oil invoke the same level of toxicity, the shift in the nature of exposure becomes an important determinant of effect. That is, are potential toxic impacts being shifted from surface waters to the water column?

The concept of LC_{50} has been discussed previously in other sections. Briefly, it involves the exposure of a population of test organisms to a constant concentration of a compound for a specific period of time, usually 24-, 48- or 96-hours. By extrapolating the toxicity obtained from a number of different concentrations, the exposure level at which half the test organisms die is obtained. Anderson et al. (1984) noted that this method, while straightforward in concept, has a number of shortcomings, particularly with respect to assessment of petroleum compounds:

> (LC_{50}) tests were usually conducted in closed ("static") systems without feeding test organisms or replenishing the toxicants. As more chemical analyses were conducted, investigators began to realize that significant amounts of many toxicants sorbed to the walls of vessels, evaporated, and were taken up by organisms. In tests with petroleum, there were also problems with droplets moving to the surface (forming slicks) and numerous alterations related to different specific components.

Many of the LC_{50} tests performed and reported in the literature have been based on the nominal concentrations of dispersant and/or dispersed oil, and not those actually measured in the water to which organisms were exposed (nominal concentrations are those based on the volume mixtures of contaminants and not the concentrations in the water). This can be a fundamental source of error in estimating exposure concentrations, due to the tendencies of hydrocarbons either to adhere to test equipment, as well as the difficulties in getting largely hydrophobic ("water-hating") compounds to dissolve in test waters.

In order to address some of the inadequacies of classical LC_{50} toxicity testing and to provide a basis for comparing results from many studies using different exposure times or concentrations, Anderson et al. (1984) demonstrated the concept of the toxicity index. The toxicity index considers exposure duration and toxicant concentration to be equal factors in toxicity. The index is expressed as the product of the two, with values reported in ppm days or ppm hours. Under the assumptions of this approach, a two-day exposure to 10 ppm of a contaminant (yielding a toxicity index value of 20 ppm day) should produce the same toxic effect as a five-day exposure to 4 ppm, or a ten-day exposure to 2 ppm.

Singer et al. (1990) reviewed previously reported results as well as new data generated in a study of dispersant toxicity to California marine organisms, and portrayed calculated toxicity index values in a graphic reproduced below as Figure 5-10.

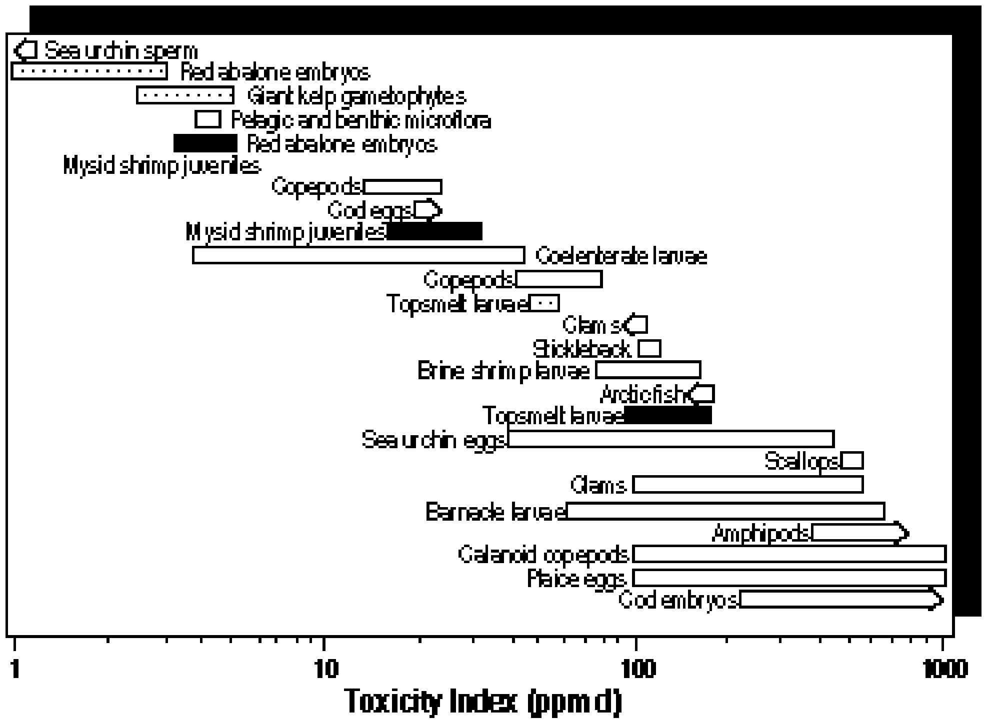

Figure 5-10. Comparison of toxicity index calculations for Corexit 9527. Shaded and solid boxes indicate no observed effects concentrations and median effect ranges, respectively, obtained by Singer et al. for California species. Arrows indicate toxicity values reported with unspecified upper or lower limits. Source: Singer et al. (1990).

Although this comparison indicated that toxic effects in some organisms might be expected at low concentrations that could be encountered in the environment following a dispersant application, Singer et al. cautioned that there may be problems with the concept underlying the graphic. They questioned the validity of toxicity index data based on results they obtained for California species in the course of their study. Figure 5-11 shows toxicity index values obtained for two species, one a mysid crustacean, and the other a fish. While the results for the mysid appeared to support the toxicity index concept, those for topsmelt clearly did not. The index values increased with time, suggesting that the fish could mitigate the effects of dispersant exposure with time. Singer et al. commented:

> Our data suggest that the toxicity index may overlook the complex physiological and biochemical processes which affect toxicity and thus may not provide truly comparable values across species.

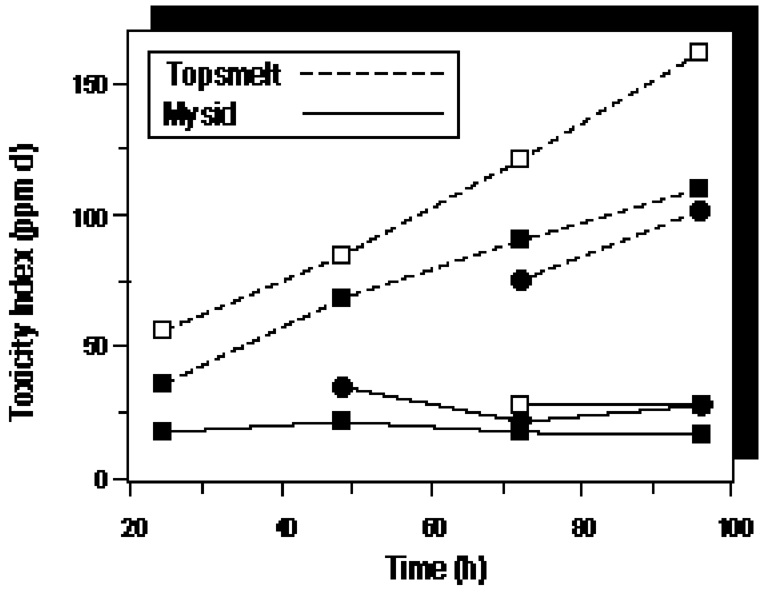

Figure 5-11. Comparison of daily toxicity index values for two California species, one a mysid and the other a fish. Source: Singer et al. (1990).

The methods employed by Singer and his colleagues in the state of California attempted to address many of the inadequacies of other techniques. Nevertheless, while no laboratory evaluation will be perfect in its simulation of true environmental conditions, useful insights may be obtained from studies employing older methods that have since been found to be biased. Results from a number of different types of toxicity studies, including those employing "classical" methods of assessing acute toxicity, will be presented in this chapter; it is important to remember limitations and shortfalls of these approaches. It would appear that more recent investigations, particularly in the state of California, may give a more accurate picture of dispersant toxicities that might be expected under realistic conditions of exposure. Results from the latter investigations will also be discussed later in this section.

A review by Wells (1984) consolidated a large amount of dispersant toxicity information available at the time. In his paper, Wells focused on the toxicity of Corexit 9527, although information for other formulations is included as well. Wells summarized threshold effect concentrations from the review of results for organisms ranging from protozoans to birds (Table 5-2).

Table 5-2. Summary of threshold effects concentrations, from Wells (1984). Expected water column concentrations for dispersants, from Wells (1984) and Peakall et al. (1987).

Effect	Concentration (mg/l)
Lethal thresholds	$<10^1 - 10^2$, some; $10^2 - 10^4$, most
Sublethal thresholds	$<10^2$ (short exposures), some; $>10^2$, most
Expected initial concentrations in water column	$0.1 - 10^2$

Based on this review by Wells, most of the threshold concentrations reported for both the lethal and sublethal effects evaluated were above those anticipated or found to occur after field applications of dispersants. However, Wells noted the need for more information in several areas related to toxicological evaluations of dispersants. Several recommendations were made:

1. Toxicity studies with dispersants should attempt to relate effects and their thresholds to specific compositions or major components of dispersants.

2. Studies with dispersants and dispersed oil mixtures should include early life stages of commercial and ecologically important species from vulnerable habitats and the measurement of key processes known to be sensitive to dispersants and hydrocarbons (behavior, respiration, molting, fertilization, early embryonic development).

3. Factors influencing toxicity thresholds of dispersants should be identified and quantified.

4. Toxic actions of dispersants and their components should be studied in detail at realistic exposure concentrations, under simulated and actual field conditions. Comparisons should be made between estimated exposure concentrations of dispersant components in surface waters and in intertidal areas, and between the lowest concentrations required for acute lethal effects and those required for sublethal effects.

5. Site-specific hazard assessments should be conducted prior to wide-scale usage. Facts and principles of dispersant toxicology must be applied in selection of governmental licensing or acceptability tests.

Many of the difficulties inherent in evaluating the toxicological implications of oil dispersant use were addressed in a study by Wu (1981). Wu investigated the toxicities of a true oil dispersant (BP 1100X) and a surface active agent (Shell Herder) on 18 marine species from different taxa, and found that toxicities depended very much upon the species tested. The organisms tested included fish, tunicates, urchins, starfish, barnacles, shrimp, bivalve molluscs, and gastropods. The oil used was diesel oil at 1000 ppm concentration. Some species showed high sensitivities to BP 1100X and low with Herder, while for others the opposite was true. Results are summarized below in Table 5-3.

TABLE 5-3. Percentages of mortality for different species with treatment of BP 1100X and Shell Herder (1000 ppm dispersant/surfactant + 1000 ppm diesel oil). Source: Wu (1981).

Organism	Shell Herder + diesel	BP1100X + diesel	Significant/Non between treatments
Fish			
Callionymus richardsonii	50.0 ± 14.1	40.0 ± 14.1	NS
Siganus oramin	82.0 ± 21.9	3.0 ± 2.7	S
Tunicate			
Styela plicata	4.0 ± 5.5	36.0 ± 11.4	S
Urchins			
Anthocidaris crassispina	0	0	NS
Echinodermata mathei	0	0	NS
Salmacis bicolor	0	0	NS
Starfish			
Archaster typicus	0	0	NS
Barnacle			
Balanus amphitrite	0	0	NS
Mantis shrimp			
Oratosquilla oratoria	40.0 ± 7.1	82.0 ± 8.3	S
Bivalves			
Anadara broughtonii	2.5 ± 3.5	1.5 ± 3.4	NS
Anadara granosa	2.0 ± 4.5	0	NS
Barbatia obliquata	2.0 ± 4.5	4.0 ± 5.5	NS
Paphia undulata	46.0 ± 13.3	45.0 ± 12.7	NS
Perna viridis	0	0	NS
Septifer bilocularis	0	0	NS
Gastropods			
Babylonia areolata	0	0	NS
Babylonia formosae	0	0	NS
Nucella clavigera	0	0	NS

The table above shows the wide range of results obtained among the different organisms. Toxicities were very much dependent on species and the product tested, and Wu commented on the implications for evaluating toxicity of products such as dispersants:

> The large differences in susceptibility within a single animal group found in the present study. . .indicate that neither the absolute nor relative toxicity of an oil dispersant can be ascertained by selecting one "representative" species. Due to the time and manpower involved, however, it may be impractical to test each product against a large number of species in order to determine its toxicity. Even if this is possible, the criteria of passing and failing a dispersant/surface active agent would be difficult to establish, since the product might be toxic to some of the species but not to the others.
>
> . . .It seems logical, and more meaningful, from an environmental point of view, that toxicity tests should be performed on species which are ecologically important (e.g., "key species" of a community or population with a high energy flow value) in identified receiving environments, rather than on some animals which are easy to obtain and maintain in the laboratory.

Specific regional studies on a variety of organisms, as advocated by Wu, have been undertaken by California researchers. Investigations of this type will hopefully enable more realistic and applicable toxicity data to be factored into dispersant use decisions. The California tests are summarized below.

Toxicity to California marine organisms

Singer et al. (1990) examined the toxicity of constant low-level exposures of Corexit 9527 to sensitive life stages of four California marine organisms: giant kelp, *Macrocystis pyrifera*; red abalone, *Haliotis rufescens*; mysid crustacean, *Holmesimysis costata*; and topsmelt, *Atherinops affinis*. It was found that the organisms had varying degrees of sensitivity to the dispersant. Juvenile red abalone and the newly released zoospores of giant kelp were most sensitive, with no observed effects concentrations (NOEC) in a range between 0.63 to <2.35 ppm. Larval topsmelt were the least sensitive, with NOEC ranging between 12.3 and 14.2 ppm.

From an applied perspective, it should be remembered that in the above study, the test organisms were continuously exposed over periods of time ranging from 24 to 96 hours. This is common for many studies of toxicity, but not necessarily realistic. In an actual dispersant application scenario, exposures to organisms would be expected to be transient and continuously declining as the dispersant and oil-dispersant mixtures are themselves dissipated in three dimensions. Resultant toxicities would be dependent upon concentration-time profiles. An article by Peakall et al. (1987) included a summary of studies that have examined dispersant and oil-dispersant concentrations under treated oil slicks. In these studies, total initial hydrocarbon concentrations were found to range between 1-100 ppm. However, it was recognized that many constituents of the dispersed oil which rapidly dissolve and/or evaporate would decline to parts per billion—or lower—levels within minutes or hours.

Tjeerdema et al. (1990) attempted to address some of the inadequacies of traditional toxicity methodologies by conducting a study using the same materials and test organisms as Singer et al. above, but exposing the biota to spiked concentrations of Corexit 9527. In other words, an initial exposure concentration of dispersant was continuously diluted, in order to simulate the situation organisms might be expected to realistically encounter during a real application of dispersant.

Tjeerdema et al. found that the test organisms reacted differently, both qualitatively and quantitatively, to spiked exposures than they did to constant concentrations. *Haliotis* (red abalone) were most sensitive to the spiked exposure, as was the case in the continuous concentration experiment. NOEC ranged between 5.3 and 8.4 ppm. *Macrocystis* zoospores also reacted similarly in both exposures, with NOEC in the spiked experiment between 12.2 and 16.4 ppm. The mysid *Holmesimysis* had NOEC in the range of 8.4 to 20.5 ppm, and the topsmelt *Atherinops* between 31.0 and 89.8 ppm; however, in the latter two cases, the shape of the dose-response curve was qualitatively different than in the constant exposure. That is, the relationship was exponential in character, suggesting that a threshold for effects may exist. Below this threshold, the animals may be able to survive and adapt to dispersant exposure, but beyond, they are stressed beyond survivability even if the exposure is discontinued. Mysids survived the initial spike relatively well, but showed a delayed mortality 72 to 96 hours after exposure. Topsmelt, on the other hand, showed a greater susceptibility to the initial spike but those surviving the spike generally survived the entire test period.

Tjeerdema et al. summarized the implications of their results:

> Data from this study show that inferring toxicity of dispersants in actual use situations from laboratory collected, constant exposure data may lead to erroneous conclusions regarding environmental impacts. We have seen that traditional constant exposure data on a particular species may not give adequate insight into delayed mortality or increased sensitivity under realistic exposures of that species. Also, while exposure tests are not perfect models of the "real world", our data suggest that even very ephemeral exposure to dispersants at field-measured concentrations may be toxic to some marine larvae. Thus, on-scene coordinators must exercise increased caution and attention to specific conditions when evaluating dispersant use.

Investigations into the effects of dispersants and oil-dispersant mixtures are summarized below in order to show the range of organisms that have been studied, as well as the range of impacts noted. This is not intended to be a comprehensive review of toxicological effects studies, but rather, it is to illustrate the diversity of effort, approaches and results available (and not available) for groups of organisms. More integrative and interpretive research reviews include the previously discussed National Research Council (1989), and Wells (1984). The former is a particularly nice overview of many aspects related to dispersants and their use, and includes a good discussion of toxicity and review of relevant studies.

Mammals

Little information is available on the extent of and effects of ingestion of oil by pinnipeds and cetaceans. Even fewer studies exist for toxicological and exposure reduction implications of dispersant use. Nevertheless, because coastal waters where dispesant use would be considered are utilized by a wide range of marine mammals, including sea otters, pinnipeds and cetaceans, the potential impacts of both oiling and dispersant use should be anticipated. Results presented below necessarily focus on oil impacts to mammals, but these are relevant in that a major factor in determining the appropriateness of dispersant use in a spill situation.

Of all the marine mammals, probably the most information related to oil impacts is known for sea otters (*Enhydra lutris*). The most detailed studies to date of oil toxicology in sea otters took place during the *Exxon Valdez* spill in Alaska. Unfortunately, information from these studies has been slow to emerge from the morass of litigation and natural resource damage assessment. Some observations, however, were presented at a 1990 Southern California Academy of Sciences conference on wildlife impacts resulting from the *Exxon Valdez* spill, by Terrie M. Williams of International Wildlife Research. These included the following:

- Oil was problematic to sea otters because they spend such a large portion of their lives at the surface.
- Very little was known about otters that were brought in from the field either for necropsy or for cleaning.
  Lack of knowledge on why otters had died, how the oil had killed them, and on routes of exposure
- Three critical medical factors appeared to contribute to cause of death in otters:
  1. Unstable temperature, both high and low
  2. Hypoglycemia (low blood glucose)
     Common in first days of the spill
     Lightly oiled animals had >140 mg/decaliter (dl) glucose

Moderately oiled animals had 80 mg/dl
Heavily oiled animals had 60 mg/dl
Undetermined whether glucose depression resulted from inability to absorb food, impaired ability to hunt, or other reason

3. Emphysema
   Limited to first weeks of spill
   Was devastating to otters
   Sections of lungs blown out, resulted in leaking of gases into body cavity
   Some theories that toluene, benzene-type vapors caused emphysema

- Most serious impacts were observed early in the spill

The first and last observations are probably of greatest relevance in relating dispersant use to impacts on sea otters. Clearly, experiences from the *Exxon Valdez* and elsewhere have shown that sea otters are particularly at risk from oil exposure. In addition to the physiological effects cited above, the impacts on the ability of otters to thermoregulate are severe: 20 percent oil cover on a sea otter results in a doubling of metabolic rate, and the resultant energy expenditure to maintain body heat exceeds that attainable by foraging (Michael Fry, personal comm. 1991).

Because animals suffered the most severe impacts early into spill events when the oil is most toxic, quick response to prevent exposure is of primary importance. The use of *effective* dispersants would be desirable in order to reduce the extent of that exposure. However, the effects of dispersant exposure on sea otters has not been well researched. It has been speculated (Fry, personal comm. 1991) that impacts from oil and the detergents present in modern dispersants may be equally harmful to sea otters, in terms of effects on pelt insulation. Further research efforts are needed, even for this relatively well-studied marine mammal.

Information for other mammals, including the pinnipeds and cetaceans, is scant. For pinnipeds, it is known that external oiling has little impact on thermoregulation due to the presence of blubber layers. In the *Exxon Valdez* spill, the effects on harbor seals were remarkably less severe than for sea otters. There were no observed thermoregulatory problems, although some corneal lesions attributable to oil exposure were observed. Internal effects of oil ingestion were apparently not serious. Although some pups with elevated blood hydrocarbon levels lost weight and appeared unhealthy for a time, all recovered.

Experiences such as these for harbor seals suggest there is less reason to consider the use of dispersants when the marine mammal resource at risk is a pinniped species, as opposed to sea otters.

The limited research performed with cetaceans suggests that they are less at risk during an oil spill than other living marine resources. Geraci and St. Aubin (1982) found that bottlenose dolphins (*Tursiops truncatus*) could detect as well as avoid oil on the surface of the water.

They also investigated the effects of petroleum hydrocarbons on the physiology of cetacean skin, which is structurally and functionally unique among mammals. Although bottlenose dolphins were again the principal study species, others such as Risso's dolphin (*Grampus griseus*) and sperm whale (*Physeter catodon*) were included opportunistically. Changes in a number of parameters were examined, including skin color, heat of exposed area, cellular damage and healing time, healing time of previously damaged skin, damage to functional biochemistry of cells. Some minor changes were observed for each parameter following exposure to petroleum, but for the most part these were transient in nature.

Geraci and St. Aubin (1982) also studied the potential for oil fouling of baleen filters that mysticete cetaceans use for feeding. It was found that light- to medium-weight oils reduced water flow through baleen plates of fin and gray whales, but that flow returned to normal within 40 seconds. Fouling with a heavy Bunker C product restricted flow for up to 15 minutes, but even though plates were noticeably oiled, flow returned to normal. Clearance of the baleen fibers occurred within 15-20 hours, even with heavier-fraction oils. Impacts on contamination of food items or physical adherence of food to the plates was not examined.

In summary, Geraci and St. Aubin concluded that impacts on cetaceans from oil spills would not be expected to be severe, although it was recognized that many areas of oil impacts have not been studied. However, based on the lack of a recognized severe risk to cetaceans from oil exposure, rationalizing the use of dispersants based on a perceived threat from oil to these marine mammals probably is not warranted.

It is very clear that the effects of dispersants on marine mammals is poorly described. What little guidance that exists for considering potential impacts on marine mammals is based on speculation or extrapolation. Neff (1990) summarized the situation:

> Virtually nothing is known about the effects of oil dispersants on marine mammals, except as they are used to clean oil-fouled sea otters. By removing spilled oil from the sea surface, dispersants obviously reduce the risk of contact. The oil remaining, on the one hand, would be less sticky, and therefore less likely to adhere to fur, skin, baleen plates, or other body surfaces. On the other hand, the surfactants in dispersants may remove natural oils from marine mammal fur, thereby decreasing its insulating properties. Cleaning oiled beaches and rocky shores with dispersants may be an effective means of preventing oiling of pinnipeds that may wish to haul out there. More work needs to be done before we can adequately weigh the advantages or disadvantages of using dispersants in such habitats.

With the exception of sea otters, it would appear that exposure of most marine mammals to oil does not result in severe impacts. The ability of marine mammals to avoid oiled areas and the lack of demonstrated toxic effects suggest that there may be less need to consider dispersant use for protection of mammals than there may be for other resources. However, special situations, such as the presence of large numbers of sea otters and/or haulout and breeding areas in a spill area, may provide substantial impetus to consider dispersant use.

Birds

The effects of oil on seabirds are both well known and well described, and are discussed elsewhere in this text. Studies examining dispersant impacts, either alone or in concert with oil, are much less common. Peakall et al. (1987) summarized the available information.

Reproductive impacts on four species of birds exposed to various combinations of oil and dispersant were presented. In the mallard (*Anas platyrhynchos*), doses of Prudhoe Bay crude oil, Corexit 9527, and oil-dispersant mixtures (5:1 and 30:1 oil:dispersant) applied to the surface of eggs all resulted in marked embryotoxicity, with greater effects noted if the application was made early in incubation. The 30:1 oil:dispersant mixture was found to be significantly less toxic than the oil alone. In a related experiment, exposures were made to more closely resemble field conditions by exposing mallards to water troughs with oil and dispersant mixtures. In this case, the hatchability of eggs exposed to oil alone was reduced, while that from Corexit and oil-Corexit was not significantly different from unexposed controls. However, the results were variable enough for the investigators to conclude that crude oil-Corexit mixtures probably pose the same threat to eggs that oil alone does.

Studies on weight gain among both mallards and herring gulls exposed to oil and oil-dispersant mixtures showed that in mallards, no effect was noted for either oil or the mixture. In gulls, a significant decrease in weight gain was found for both oil exposure and oil-dispersant exposure, but no difference between the two exposures.

Only one study that examined oil and oil-dispersant effects in the field was noted by Peakall et al. In this investigation, Leach's storm petrels were given either external or internal doses of Prudhoe Bay crude or oil-Corexit 9527. No effects were seen in the internal dosing, but the highest concentration exposure of external dosing with oil-dispersant resulted in significantly higher nest desertions during brooding. No significant effects were observed with oil alone. Hatching success for both oil and oil-dispersant treated adults was similarly reduced.

Physiological studies on herring gulls and mallards showed that oil alone and oil-dispersant mixtures had similar effects on birds. This implied that the assessment of exposure hazard was therefore dependent on the nature of exposure. That is, are birds more likely to experience a higher degree of exposure through oil remaining on the surface, or through oil and oil-dispersant mixtures resulting from a dispersant application?

Because many seabirds are most at risk in an oil spill situation from exposure to oil on the surface of the water, it is a reasonable assertion that in theory, the use of dispersants should be advantageous because it would decrease the amount of oil contacted at the surface. However, unless the dispersants are highly effective, Peakall et al. suggest that the differences in oil exposure at the surface are very small, and likely to be negligible in terms of the overall oil hazard to the birds. Theoretical calculations by Peakall et al. on exposure occurring as a seabird dives through a dispersed oil mass indicated that it is likely to be minimal.

Peakall et al. came to two major conclusions as a result of their review and research. First, they found little evidence of a synergistic increase in oil toxicity to birds when oil was combined with dispersant. Second, in order to significantly reduce surface exposures of seabirds, dispersants need to be highly effective. Recent research has suggested that the latter condition is not a reality. For example, Fingas et al. (1991a) tested four dispersants with 20 different types of crude oils and refined products, and obtained efficiencies of dispersion ranging from 1 percent to 96 percent. The nature of the oil product appeared to be a greater determinant of efficiency than did the dispersant employed.

Jenssen and Ekker (1991) found that for eiders (*Somateria mollissima*) and mallards (*Anas platyrhynchos*) whose plumage was fouled with oil (Stratfjord A crude) or crude oil mixed with the dispersants Finasol OSR-5 or OSR-12, oil-dispersant mixtures were more potent in reduction of thermoregulatory capability. Both exposures resulted in a reduction in the water-repellency of plumage, a resultant increase in plumage water absorption, an increase in heat loss, and a compensatory increase in heat production. However, much smaller amounts of the oil-dispersant mixtures were required to cause the effects. Jenssen and Ekker speculated that the reason for this result may be that surfactants in the dispersants more readily adhere to the feather structure or bind to waxes that birds preen into their feathers.

It was also found that the different species were affected to different degrees, with eiders more sensitive to the oil-dispersant mixtures than mallards. An explanation for the difference may lie in differences in feather structure, and suggests more broadly that different species of aquatic birds may respond differently to contamination of plumage.

Jenssen and Ekker ended their article by explicitly addressing the question, "Should oil spills at sea be treated with chemical dispersants in order to reduce their impact on bird life?" They noted that their results implied that in order to minimize the impact of a spill on birds, the concentration of treated oil needs to be very low by the time it reaches flock of birds at sea. Results of effectiveness studies were cited in which the action of dispersants was indeed very rapid, with resulting concentrations in chemically treated slicks very low (Fingas et al. 1991a, however, dispute claims of high dispersant efficiencies in field tests). At face value, therefore, dispersant use would seem to be advisable for protection of birds, even in light of the study results suggesting a higher potency of dispersed oil for adversely impacting thermoregulation.

National Research Council (1989) discussed the implications of dispersant inefficiency on bird exposure, and cautioned that while potential biological benefits from dispersant use exist for birds (e.g., reduction in surface oil amounts), it is also possible that residual sheen from dispersed oil slicks may cover a greater area than untreated oil, resulting in potential exposure to more birds rather than fewer.

Jenssen and Ekker also expressed concerns about potentially increased exposure to oil due to dispersant use:

> . . .one should also note that dispersants may have a secondary effect, by increasing the surface area of the slick. In a "worst case" scenario, chemical treatment of an oil slick may therefore increase the risk of exposure of more birds to less, but more harmful, chemically treated oil mixtures. Since the effect of oil-dispersant mixtures on the thermoregulation of seabirds is a function of the amount of the contaminant absorbed by the plumage, the effect is dependent on both the concentration of the pollutants in the water, and on the volume of contaminated water with which the birds come into contact.

Finally, noting the apparent differences in species effects, they conclude that until more data on impacts are available, birds should be prevented from coming into contact with chemically treated oil slicks unless the hydrocarbon concentrations are known to be very low.

Fish

National Research Council (1989) summarized the results of a number of acute toxicity tests performed on fish species. Unfortunately, these studies are somewhat dated, with most having been published in the 1970s. The summary listed results of LC_{50} tests from 13 separate studies that examined effects on 13 fish species. Eight dispersant products were tested, with exposure periods ranging between 48 and 96 hours. Values for LC_{50} concentrations ranged between 29 ppm and >10,000 ppm. The wide range of results obtained are difficult to interpret, especially given that there are many combinations of organism, dispersant, and exposure time. Unless the dispersant product/species pair happens to match the exact product/species pair of interest or concern, probably the most illuminating aspect of the tabular summary is the range of results obtained in the studies, with the implied inability to generalize about dispersant toxicity.

Oyewo (1986) performed acute toxicity tests with the fingerlings of mullet (*Mugil sp.*) and three dispersants (Conco-K, Foremost, and BP 1100X) calculating LC_{50} concentrations for three exposure periods (24-, 48-, and 96-hour). There were significant differences in LC_{50} concentrations among products. For example, in the 96-hour test at about 36 parts per thousand salinity, the LC_{50} concentration for Conco-K was 4.60 ppm, for Foremost was 52.0 ppm, and for BP 1100X was 151 ppm. The relative relationships among the three products were consistent across all exposures (i.e., toxicity of Conco-K > Foremost > BP 1100X), and in fact, the absolute values of the LC_{50} concentrations were essentially the same for all three products across the range of different exposures. Salinity differences did not appear to influence the results. The study results suggest the importance of not extrapolating a general condition from the results of toxicity testing for a single product.

Akintonwa and Ebere (1990) tested the toxicity of crude oil (Asabo 16c) and two dispersants (Conco-K and Teepol) to two species of freshwater fish (*Barbus sp.* and *Clarias sp.*) both discretely and in combination. They found that the two dispersants were much more toxic to the fish than crude oil alone, and that when the dispersants were used in combination with oil, the toxicity of the oil increased. They concluded that combining crude oil and dispersant resulted in a higher toxicity than that from the dispersant alone.

Crustaceans

Ahsanullah et al. (1982) conducted standard LC_{50}-type toxicity tests using a hydrocarbon-based dispersant (BP/AB), Kuwaiti crude oil, and an oil-dispersant mixture. The key finding in this study was that combining oil with dispersant increased the toxicity of the oil to a crab species by a factor of 16. The results suggested that the physical effect of the dispersant in emulsifying the oil resulted in the increase in toxicity, with the broader implication being that toxicity is in effect a measure of the the efficiency of the product: the more efficient the product, the more toxic the oil-dispersant mixture.

However, Ahsanullah et al. included some precautionary comments about extrapolating the results to a real-world situation:

> It is difficult to apply these results to an oil spill situation in the marine environment because the laboratory conditions do not replicate the hydrographic characteristics of the affected areas. This includes wave action, dispersal by currents and the spatial separation of the fauna from oil on the surface of the sea or in the case of littoral animals, the physical coating of the body surface with oil.

As an additional component of the fish study cited above, Oyewo (1986) also tested three dispersants for acute toxicity to hermit crabs (*Clibinarius africanus*) and obtained results qualitatively similar to those for the fish tested (i.e., the toxicity relationship of Conco-K > Foremost > BP 1100X). In 33.5 parts per thousand salinity and 24-hour exposure, the LC_{50} concentrations obtained were, for Conco-K, 9.2 ppm; for Foremost 19.4 ppm; and for BP 1100X, >30,000 ppm. The results in different exposures and the different salinity were somewhat more variable than was the case for the fish, but overall demonstrated the same trend.

Oyewo also cautioned about the extrapolation of these kinds of results to the real world:

> It is necessary to emphasize that results of acute toxicity tests cannot, alone, form the basis of any decision on the use of oil dispersants since several other considerations are important in the overall decision framework. . .However, relative toxicity data plus a detailed knowledge of field effects is a useful combination for ecological predictions and therefore invaluable in making decisions on the use of oil dispersants.

Anderson et al. (1984) examined the seasonal effects of dispersed oil exposure on toxicity to coonstripe shrimp (*Pandalus danae*). Prudhoe Bay crude oil was used in the test, with two unspecified dispersant products. Differences in effects were observed between the two dispersants, particularly in winter exposures. Although significant differences in toxicity were not found between the dispersants in summer exposures, the overall levels of toxicity in summer were significantly higher.

Molluscs

Hartwick et al. (1981) studied the effects of Alberta crude oil, Corexit 9527, and oil-Corexit mixtures on several aspects of littleneck clam (*Protothaca staminea*) behavior and physiology. They found in both laboratory and field experiments that Alberta crude oil alone (1000 ppm), or low concentrations (<10 ppm) of Corexit 9527 were not greatly harmful to the clams. The lack of sensitivity to crude oil contrasted to results from other researchers that had suggested a particular susceptibility in molluscs.

It was also determined that the dispersant and oil-dispersant mixtures were more toxic to clams than oil alone. Mortality was observed when clams were exposed to 100 ppm Corexit 9527, and was highest in both the laboratory and in the field when a mixture of 100 ppm Corexit 9527 and 1000 ppm crude oil was used. Hartwick et al. also found variable results between the laboratory and the field:

> It was. . .apparent that the percentage mortalities resulting from the field experiments were much lower than those from the equivalent laboratory tests. Such discrepancies demonstrate the difficulty in extrapolating laboratory results to natural spill conditions.

Some impact on the settlement of clam larvae was noted with oil-dispersant mixtures over oil alone. In addition, hydrocarbon analysis of the substrate in experimental plots showed that residues penetrated deeper and were measurable for longer periods of time in oil-dispersant treated plots. The overall implications of the study results were that the impact of oil spill alone on the littleneck clam could be expected to be small. However, the use of Corexit 9527 as a dispersant may augment adverse impacts by reducing the recruitment of larvae, and by increasing the retention time and penetration depth of hydrocarbons into the substrate.

Ordzie and Garofalo (1981) examined the effects of oil (Kuwait crude), dispersant (Corexit 9527), and oil-dispersant mixtures on scallops (*Argopecten irradians*) and two predators, a drill (*Urosalpinx cinerea*) and starfish (*Asterias forbesi*). Different susceptibilities were found for the three organisms. Scallops were found to be most sensitive to dispersant and oil-dispersant mixtures, starfish were sensitive to dispersant only, while the drill was insensitive to all test mixtures.

Similar to results found by Anerson et al. (1984) for shrimp, there appeared to be a significant influence of water temperature on the degree of toxicity observed. Scallops were found to be most sensitive at water temperatures encountered in the summer, and less so at winter temperatures. This seasonal sensitivity was found to be dramatic: dispersant concentrations not lethal to scallops at winter temperatures caused >50 percent mortality at summer temperatures. The predators were affected in an opposite fashion, with treatments having a lesser impact at summer temperatures. However, sublethal effects on behavior (ability to recognize prey items) increased in predators with increasing temperature. Ordzie and Garofalo summarized the implications of their study:

> In order to accurately assess biological effects of a pollutant event, we need to know susceptibilities of animals for different seasons. . .Although temperature of ambient water could be a significant predictor of scallop susceptibility to dispersant exposure, one should not generalise to other organisms. This issue becomes more complex because either the "pollutant toxicity" or "animal sensitivity" can be affected by temperature. Accordingly, the temperature related susceptibility can be different for each organism, making broad generalisations dangerous.

Corals

Corals, of course, are a critical habitat only in tropical coastal waters. However, review of research into oil and dispersant effects on reef building corals helps to define the range of impacts across a diversity of marine organisms. Knap (1987) studied the effects of Arabian Light crude oil and oil dispersed with Corexit 9527 (1:20 mixture, dispersant:oil) and oil dispersed with BP 1100WD (1:10 mixture). Laboratory exposures were validated in the field both in winter and summer. Knap found that the coral *Diploria strigosa* appears to be relatively tolerant to brief exposures to crude oil chemically dispersed into the water column. Exposure concentrations in field experiments ranged from 8 to 25 ppm, and length of exposures were 6 hours. However, it was also noted that many of the cryptic epifaunal organisms living in the coral reef community (i.e., polychaetes, bivalves, crustaceans) displayed a greater sensitivity to the exposures that apparently did not harm the coral itself.

A multi-disciplinary, long-term field assessment of the effects of oil and dispersed oil in Panama (Ballou et al. 1989) was interesting in that it illustrated the kinds of trade-offs that dispersant use may entail. In this study, sites with three major components—mangroves, seagrasses, and coral reefs, were exposed to both oil (Prudhoe Bay crude) and dispersed (with non-ionic glycol ether-based product) oil. It was found that untreated oil had severe effects on mangroves and associated communities and relatively minor impacts on seagrasses and corals. In contrast, dispersed oil adversely affected seagrasses and corals. This suggested that the use of dispersants shifted toxicity from one compartment (intertidal) to another (subtidal). Although the situation of dispersant application to an oil slick far offshore was discussed, it was not investigated in this study. However, based on the other results obtained, Ballou et al. felt that such an approach might minimize the extent of damage to resources in both tidal zones.

Microorganisms

Protozoans. Rogerson and Berger (1981) performed toxicological studies using Corexit 9527 and ciliate protozoa. The rationale for examining impacts on protozoa were twofold: the researchers wished to study a non-traditional experimental organism, and they also wanted to examine effects on a trophic level not often considered. Rogerson and Berger acknowledged that while ciliates were not found in great abundances in pelagic waters, they are abundant in intertidal areas and could be of some ecological importance.

Rogerson and Berger found that the most sensitive ciliate protozoan species tested yielded a threshold concentration of 100 ppm Corexit 9527, although other species tolerated levels as high as 320 ppm. However, the dispersant in combination with crude oil appeared to be much more acutely toxic than the dispersant alone. It was found that mixtures with >1.0 ppm Corexit caused the protozoan cells to lyse. Because the concentration of crude oil was held constant and the concentration of

Corexit 9527 varied, Rogerson and Berger reasoned that it was the dispersant component of the emulsion that contributed most to toxicity.

The mechanism of toxicity of the oil-dispersant mixtures was also examined. Two hypotheses were that chemical emulsifiers interact with oil to release toxic substances, or alternatively, that the mixture is made more available through dispersion of fine droplets. It was determined through studies of ingestion rates and identification of materials ingested by the ciliates that in this case, toxicity was apparently manifested through increased availability of the oil-dispersant mixture. The authors speculated that it was probable that the oil acts as a vector through which the dispersant is transported into the cell, causing the disruption of cellular membranes.

It may be important to note that this study was performed using both marine and freshwater organisms. Corexit 9527 was developed for use in the marine environment, and its effectiveness in freshwater is questionable. Although evidence was cited that toxicity testing using freshwater organisms should not lead to significant errors, the possibility that differences attributable to the test conditions cannot be overlooked.

Microbial degradation. An aspect of dispersant toxicity that is often overlooked but should be acknowledged is the impact that dispersant use may have on other important processes associated with removal of oil from the environment. In particular, Foght and Westlake (1982) found that Corexit 9527 has detrimental effects on eucaryotic processes, bacterial activity at sea, and microbial oil-degrading processes. In other words, application of dispersant products can potentially negatively affect mechanisms of biodegradation.

> The addition of relatively large volumes of carbon-rich dispersants to an oiled environment already having a very high carbon to nitrogen. . .ratio (which is not suitable for rapid microbial growth) further stresses this environment. The beneficial effects of dispersants in providing more oil surface for microbial growth is countered by the additional stress on the nitrogen-phosphate level of the environment by the addition of a biodegradable dispersant. . .This stress could result in a delay of the oil-degradation process.

Another study by Bhosle and Mavinkurve (1984), using four unspecified dispersants on Saudi Arabian and Bombay High crude oil, elicited mixed results, in which some dispersants in combination with Saudi or Bombay crudes either inhibited or accelerated biodegradation processes by one of two bacterial species. Reduction in biodegradation processes was thought to result from a preferential utilization by microbes of carbon sources provided by the dispersant over those in oil. Enhancement of biodegradation rates was also observed, possibly due to the increase in oil surface area mentioned in the previous study.

Plants

Although most of the research on biological impacts of dispersants and dispersed oil has examined effects on animals, some plant species have also been studied. The overview of toxicity provided in National Research Council (1989) summarizes the results of dispersed oil toxicity studies for phytoplankton, diatoms, and vascular plants. Of eleven studies, ten found that the toxicity of dispersed oil was greater than that for oil alone. However, the results of many of these investigations were called into question by the National Research Council because of the use of nominal exposure concentrations as opposed to measured concentrations. The studies which measured concentrations in the water yielded mixed results, with two studies indicating dispersed oil as more toxic than oil alone, one suggesting oil alone as more toxic, and one showing them to be equally toxic.

Much of the research available for evaluating the effects of oil dispersants on plants has focused on tropical and subtropical species. For example, Thorhaug and Marcus (1987) studied three seagrass species found in the Caribbean and subjected them to mixtures of three commonly stockpiled dispersant products (Corexit 9527, Arcochem D609, and Conco K(K)) and two crude oils (Louisiana and Murban). They determined that at recommended application levels, no significant mortalities occurred. Higher concentrations, about an order of magnitude above recommended application levels, resulted in the deaths of more sensitive species, especially with longer exposures. Widely different results were obtained with different dispersant products, with Conco K(K) causing a consistently higher degree of mortality in all three seagrass species. The two crude oils yielded similar results.

A number of studies have examined effects of oil (South Louisiana crude) and dispersants on mangroves. Teas et al. (1987) found that crude oil caused a significant mortality to treated trees. The use of an unspecified non-ionic water-based dispersant sprayed onto previously oiled mangroves increased this mortality. Application of oil predispersed with a glycol ether-based product had no effect in reversing the mortality attributable to oil, although mortality was not increased by dispersant use. These results suggested that because oil exposure results in significant impacts on mangroves, all efforts should be made to prevent contact. Use of a dispersant, particularly a glycol ether-based product, may be justified as part of the response, since its effects appear to be no worse than the oil itself.

A longer term approach to assessment of the effects of dispersant use among mangrove trees was undertaken by Wardrop et al. (1987). They evaluated the toxicities of Arabian Light crude oil, Tirrawarra crude oil, the dispersant BP-AB, and oil-dispersant mixtures on mangroves in a fringing Australian marsh. Sublethal effects such as defoliation, leaf damage, pneumatophore damage, flowering and fruiting were monitored for three years. The results were interesting in that initial toxicity of the oil was apparently increased through the use of a dispersant, but after three months those mangroves treated with dispersed Arabian Light showed a higher degree of productivity over both Arabian Light crude alone and the unoiled controls. This apparent growth stimulation had been reported elsewhere for mangroves exposed to various hydrocarbon products. The Tirrawarra crude mixtures did not show a similar increase in growth, and in fact, produced somewhat fewer leaves.

Summary

Unfortunately, it is not possible to present a rote formula for determining ecological consequences of the use of dispersants during a spill situation. As should be apparent from the examples cited above, the effects are highly dependent on a number of factors, some of which are relatively undefined in terms of their importance.

As a spill responder, it will not be possible for you to anticipate all of the implications of dispersant use. However, keeping in mind some of the insights that have been learned may help in the decision-making process.

- The number of combinations of oil, dispersant, organism, life stage, nature of exposure, time of year, etc. that are possible in an area make a prediction of the ecological impacts of dispersant use very difficult. Several studies suggest that effects can vary significantly with different combinations of parameters, usually making generalizations inappropriate.

- The common wisdom in the case of the newer generation dispersants is that they are no more toxic than crude or refined oils to which they might be applied, and that toxicity resulting from an oil-dispersant mixture is largely attributable to the oil component. Some recent studies suggest otherwise, but more carefully designed and administered investigations clearly would be useful.

- Conceptually, the use of dispersants moves an oil product from one physical environment (the air-water interface) to another, or others (the water column or the benthic environment). However, no dispersant is 100 percent effective; application will result in variable amounts in each physical compartment, with resultant impacts proportional to the partitioning.

- Laboratory studies suggest that the toxicity of dispersants is correlated with efficiency: the more efficient a product is in moving oil into the water column, the greater the toxicity to organisms in the water column or in the benthos.

- It is difficult to extrapolate results from the laboratory to anticipated results in field exposures. Comparison of such results within the same study show a wide variation, with field mortalities attributable to exposure lower than those in the laboratory. However, some methods employed in these assessments may introduce biases that inaccurately portray toxicities.

- Certain life stages of organisms, particularly early reproductive stages, appear to be most at risk from exposure to dispersants.

- Mature life stages of animals are more tolerant to exposures to oil-dispersant mixtures. However, consideration of life cycle timing is critical, since physiological stresses imposed by reproductive or other activities may increase the susceptibility to both oil and dispersants.

- Dispersants can either enhance or inhibit biodegradation of oil, apparently depending on the dispersant product, the oil, and the specific bacteria involved.

There are distinct advantages in planning for dispersant use. The need to apply a dispersant on spilled oil very early into the event in order to maximize the efficiency of dispersion is the major motivating factor for anticipating conditions in specific regions. An integral part of this process should be the explicit consideration of ecological impacts, which may involve fairly detailed resource surveys and toxicological studies of effects on organisms of concern. Ideally, this would include:

- Identification of sensitive life stages and commercially important marine species for discrete areas of the coast.
- Critical periods of time for those species that may affect sensitivities to both oil and dispersants.
- Laboratory and/or field evaluations of the effects of oil, dispersant, and oil/dispersant mixtures, using products that could be transported or used in the event of a spill.

Although the collection and interpretation of this information can be both time-consuming and costly, it is a prerequisite to assessing ecological trade-offs realistically for the use of dispersants to treat an oil spill. An observation by Anderson et al. (1984) seems to be valid for the current situation in evaluating dispersant toxicity:

> . . .both field measurements of dispersed oil and estimates of dilution rates within a specific body of water can play an important role in estimating the impact on local species. Such assessments can be made after a spill, but it is our hope that our state of understanding will advance to a level that will allow us to accurately predict the comparative hazards of no action versus dispersant application. Only after more data are gathered. . .on a variety of organisms and ecosystems will we be in a position to make this type of accurate assessment.

Dispersant use guidelines

There are a number of methods for oil spill response and cleanup, both on the water and on shorelines. These range from doing nothing, to strictly mechanical means, such as booming or skimming, to chemical methods exemplified by the use of oil dispersants or elasticizers, to biological treatments like fertilizers or microbial mixes to enhance biodegradation. When a spill occurs, some sort of evaluative framework must be used to determine what approaches are to be used. Decision-making methods that have been formulated (usually decision trees) to provide a structure for crafting approaches generally incorporate evaluation of the use of dispersants. The decision of whether to apply dispersants involves considering the logistical and physical constraints on their use, as well as biological restrictions. Fraser (1989) provides a good overview both of oil spill decision-making methods in general, and dispersant-use guidelines in particular. He noted that the mandate to consider the anticipated outcome of dispersant use lacks specific direction:

> Most of the published decision diagrams show dispersant use as an alternative to mechanical containment and recovery, assuming the mechanical means are not effective. In almost all cases, the question is posed, "Will environmental impacts associated with chemical dispersion be less than those occurring without chemical dispersion?" But (with few exceptions), no guidance is offered to the on-scene coordinator to answer this question.

Alaska and California have a fairly typical decision tree for dispersant use (Fraser 1989; Alaska Regional Response Team 1991; Figure 5-12).

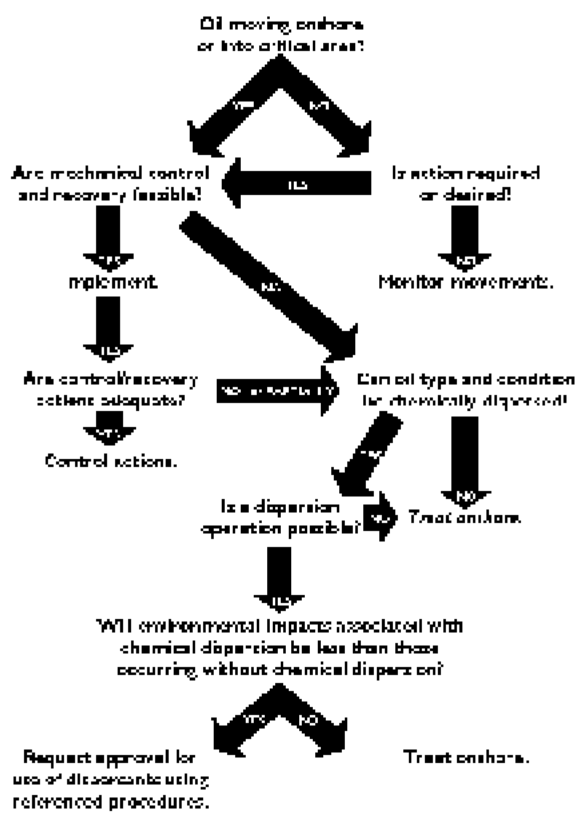

Figure 5-12. Dispersant decision matrix for Alaska and California. Source: Alaska Regional Response Team Dispersant Working Group (1991).

As this diagram shows, dispersant use will be considered as a response option only when mechanical containment and recovery actions are not considered to be feasible. It is also apparent that implementation of this decision tree requires a significant amount of information to be gathered prior to the actual time of decision, including an explicit evaluation of comparative impacts between untreated and dispersed oil. As Fraser has noted, however, no guidance is offered as to how to make this determination.

The state of Alaska has taken steps to anticipate resource impacts that may result from dispersant applications through the designation of use zones. This constitutes the major difference between the Alaska and California decision-making processes: the dispersant use criteria developed for use in Alaska classify coastal waters into three dispersant use zones. In all cases, the use of dispersants will be based on the determination that the impact of dispersants or dispersed oil will be less harmful than non-dispersed oil. The zones are defined by physical parameters such as bathymetry and currents, biological considerations such as sensitive habitats or fish and wildlife concentration areas, nearshore human uses, and time required to respond. The three zones are defined as follows:

Zone 1: Use of dispersants is acceptable. The On-Scene Coordinator (OSC) is not required to seek approval by the EPA or the state prior to dispersant use, but is required to notify both of the decision as soon as possible.

Zone 2: Dispersant use is conditional, in order to protect sensitive wildlife and other resources. The OSC is required to consult with the RRT and to obtain approval from the EPA and the state prior to use of dispersants.

Zone 3: Dispersant use is not recommended. However, dispersant use may be permitted if, on a case-by-case basis, it is determined that disturbance of the organisms and direct exposure to dispersants or dispersed oil would be less harmful than the impact of spilled oil. Consultation is required with the RRT, and approval of the EPA and state are necessary.

In Alaska, sensitive wildlife and other resources that are to be considered for dispersant use decisions have been identified as including:

- endangered or threatened species protected by Federal and state governments;

- nesting, spawning, breeding, and nursery areas for mammals, birds, fish, and shellfish;
- fish and wildlife concentration area where these animals feed, rest, or migrate;
- sensitive marine habitats, including
    - seagrass beds
    - kelp beds
    - shellfish beds
    - tidal flats
    - marshes
    - shallow subtidal areas
    - low energy bays and harbors
    - rocky intertidal areas
- aquaculture and commercial areas which are shallow enough to allow impacts from oil spills; and
- recreational and industrial areas

Evaluation of potential impacts to these resources has been factored into the use designations that have been established for specific areas, with the result being zonal configurations that may change during the course of the year to account for varying resource sensitivities. For example, the area around the Valdez tanker loading facility is designated as a Zone 1 region from October 16 to February 28, when fisheries resources such as juvenile salmon and herring spawning and rearing areas as well as fishing activities are least abundant. From March 1 to October 15, when fisheries resources and harvest activities are at a peak, the area is considered as a Zone 2 dispersant category.

Implicit in these designations are certain assumptions about the effects of dispersants on organisms and resources of interest or concern. The increased restrictions on dispersant use that are imposed on areas with aggregations of mammals, birds, fish, and shellfish imply that dispersants and dispersed oil are considered to be at least as harmful as untreated oil. The toxicity studies cited in the preceding discussion show that impacts vary widely among organisms, dispersants, oils, life stages, water temperatures, and the like, and suggest that studies directed at specific combinations that are relevant for specific areas would be useful in planning exercises. The investigations on sensitive life stages of California marine organisms (i.e., those by Tjeerdema et al. and Singer et al. discussed in the preceding section) provide a good basis for evaluation of dispersant use impacts and subsequent designation of dispersant use zones.

Research Planning, Inc. (RPI), has had considerable experience in evaluating both the effectiveness of dispersants as well as resource impacts resulting from dispersant use. RPI has been participating in the development of simplified dispersant-use guidelines (RPI 1991) that could be incorporated into a computer-based expert system for use in spill response decisionmaking. Some of the salient features of the RPI work have a broader application in formulating dispersant use guidelines include the following considerations:

1. First, determine the quick and easy answers that eliminate the use of dispersants.

   1. Is the oil dispersible? NO for light petroleum products (No. 2 fuel, jet fuel, gasoline). NO for very heavy products (heavy No. 6 fuel, Bunker C, asphalts, residuals). Possible YES for all other oil types.

   2. If the oil has formed an emulsion, then it is no longer dispersible.

   3. Is the wave height between 1 and 10 feet? If lower, then dispersants are not very effective, because of insufficient mixing forces. If higher, then dispersants are not recommended because of sufficient natural mixing, as well as logistical problems.

   4. Is sufficient dispersant available in time for use? This issue is the window of opportunity during which the oil is dispersible. The time frame depends on the meteorological conditions, and oil type. The transition is gradual.

   5. Is this in a RRT preapproval area? This is a question response personnel need to know the answer to in advance. If the answer is no then it must be determined if approval can be obtained within the time frame indicated above.

   6. Is the water depth in the spill area greater than 30 feet? If NO then dispersants are not to be used. Field studies and mathematical models show that oil concentrations under a dispersed a dispersed slick will have concentrations of 1 ppm or greater down to 30 feet. With 1 ppm set as the maximum safe concentration, dispersants could not be used in less than 30 feet, with the entire water column concentration being above the 1 ppm level.

2. Answer other predetermined questions that have been specified to eliminate the use of dispersants. For example:

1. Are there any water intakes in the area? If YES then dispersants are not to be used.

2. Are there critical subtidal resources? This includes nursery grounds, spawning aggregation areas, or other areas of particular sensitivity. If these exist in the area being considered, then dispersants are not to be used.

3. Compare subtidal and intertidal impacts of oil and dispersed oil.

1. Intertidal effects of exposure to oil - Considers shoreline sensitivity for beaches, marshes, and tidal flats. Incorporates assessment of animal sensitivity and ranking through a system examining possibility of oiling, sensitivity to oil, environmental/commercial/recreational status (i.e., endangered, commercial fishery, federally managed).

2. Intertidal/subtidal effects of dispersed oil - Shoreline impact would be expected to be reduced with increased effectiveness of the dispersant; subtidal impact may increase. Subtidal animal toxicity is calculated, and impact values assigned to the animals. Calculations include determining the ppm-hour concentrations over a 24 hour period, and comparing that to the toxicity data of the animal to determine the percent mortality at the given ppm-hours.

3. Compare the weighted values for the effects of dispersed oil and the effects of oil. The parameter with the lower number has the least adverse effect.

In summary, general guidelines (i.e., decision trees) for the use of dispersants exist for many regions. Considering impacts to biological resources is a component of these guidelines, but guidance for how to do this is generally vague. By defining, in advance, those resources considered to be sensitive or otherwise of importance, and estimating or determining the effects of oil and dispersed oil on those resources, decision-makers may then define dispersant use zones that will greatly simplify dispersant use decisions during spill incidents.

Shoreline Cleanup Methods and Application

Approved Physical Methods

A wide range shoreline cleanup methods are used during oil spills. Listed below are the more commonly used methods, including the objective, description, applicable shoreline types, guidelines on when to use the method, general biological constraints, and potential environmental effects. These descriptions were initially written as part of the Shoreline Treatment Manual developed in 1989 during the first year of the *Exxon Valdez* spill cleanup program. They were revised in 1991 as part of an effort by Region III for preplanning for oil spill cleanup requirements and approvals.

1. No Action

OBJECTIVE:

No attempt to remove any stranded oil, to minimize impacts to the environment or because there is no proven effective method for cleanup.

DESCRIPTION:

No action is taken.

APPLICABLE SHORELINE TYPES:

Can be used on all shoreline types.

WHEN TO USE:

If the shoreline is extremely remote or inaccessible, when natural removal rates are very fast, or cleanup actions will do more harm than leaving the oil to be removed naturally.

BIOLOGICAL CONSTRAINTS:

This method may be inappropriate for areas where high numbers of mobile animals (birds, marine mammals, crabs, etc.) use the intertidal zone or adjacent nearshore waters.

ENVIRONMENTAL EFFECTS:

Intertidal — The same as the oil.
Subtidal — The same as the oil.

2. Manual Removal

OBJECTIVE:

Removal of stranded surface oil with hand tools and manual labor.

DESCRIPTION:

Removal of surface oil and oily debris by manual means (hands, rakes, shovels, etc.) and placing in containers for removal from the shoreline. No mechanized equipment is used.

APPLICABLE SHORELINE TYPES:

Can be used on all shoreline types.

WHEN TO USE:

Generally used on shorelines where the oil can be easily removed by this non-mechanical means. Most appropriate for light to moderate oiling conditions.

BIOLOGICAL CONSTRAINTS:

Foot traffic over sensitive areas (shellfish beds, algal mats, bird nesting areas, dunes, etc.) is to be restricted. May be periods when shoreline access is restricted (e.g., bird nesting, mammal pupping).

ENVIRONMENTAL EFFECTS:

Intertidal — Minimal if surface disturbance by cleanup activities and work force movement is limited.

Subtidal — None.

3. Passive Collection Sorbents

OBJECTIVE:

Removal of oil by sorption onto oleophilic material placed in the intertidal zone.

DESCRIPTION:

Sorbent material is placed on the surface of the shoreline substrate allowing it to absorb oil as it is released by tidal or wave action. Oil removal is dependent on the capacity of the particular sorbent, energy available for lifting oil off the shoreline, and degree of weathering.

APPLICABLE SHORELINE TYPES:

Can be used on any shoreline type.

WHEN TO USE:

When the shoreline oil is mobile and transport of oil is expected on or off the site. The oil must be of a viscosity and thickness to be released by the substrate and absorbed by the sorbent. Often used as a secondary treatment method after gross oil removal, and along sensitive shorelines where access is restricted.

BIOLOGICAL CONSTRAINTS:

None, although this method can be slow thus allowing oil to remain in critical habitats during sensitive periods of time.

ENVIRONMENTAL EFFECTS:

Intertidal — None, except for the amount of oil remaining on the shoreline after the sorbents are no longer effective.

Subtidal — None.

4. Debris Removal

OBJECTIVE:

Removal of contaminated debris and logs.

DESCRIPTION:

Manual or mechanical removal of debris from the upper beachface and the zone above high tide beyond the normal wash of waves. Can include cutting and removal of oiled logs.

APPLICABLE SHORELINE TYPES:

Can be used on any shoreline type, where safe access is allowed.

WHEN TO USE:

When driftwood and debris is heavily contaminated and, either a potential source of chronic oil release, an aesthetic problem, or a source of contamination of other organisms on the shoreline.

BIOLOGICAL CONSTRAINTS:

Disturbance to adjacent upland areas should be minimized. Foot traffic over sensitive intertidal areas (shellfish beds, algal mats, bird nesting areas, dunes, etc.) is to be restricted. May be periods when shoreline access is restricted (e.g., bird nesting, mammal pupping).

ENVIRONMENTAL EFFECTS:

Intertidal — None.
Subtidal — None.

5. Trenching

OBJECTIVE:

Remove subsurface oil from permeable substrates.

DESCRIPTION:

Dig trenches to the depth of the oil and remove oil floating on the water table by vacuum pump or super sucker. Water flooding or high-pressure spraying at ambient temperatures can be used to flush oil to the trench.

APPLICABLE SHORELINE TYPES:

Can be used on beaches ranging in grain size from fine sand to gravel.

WHEN TO USE:

When large quantities of oil penetrate deeply into permeable sediments and cannot be removed by surface flooding. The oil must be liquid enough to flow at ambient temperatures.

BIOLOGICAL CONSTRAINTS:

Trenches should not be dug in the lower intertidal when attached algae and organisms are abundant.

ENVIRONMENTAL EFFECTS:

Intertidal — On gravel beaches, there may be a period of beach unstability as the sediments are redistributed after the trenches are filled in.
Subtidal — None.

6. Sediment Removal

OBJECTIVE:

Removal of surface oiled sediments.

DESCRIPTION:

Oiled sediments are removed by either manually using hand tools or mechanically using various kinds of motorized equipment. The oiled material must be transported and disposed of off-site.

APPLICABLE SHORELINE TYPES:

Can be used on any shoreline with surface sediments. On rocky coasts, only manual removal is feasible. Equipment is to be used only on beaches, with special supervision to minimize sediment removal.

WHEN TO USE:

When only very limited amounts of oiled sediments have to be removed. Should not be considered where beach erosion may result. Care should be taken to remove the sediments only to the depth of oil penetration, which can be difficult with heavy equipment.

BIOLOGICAL CONSTRAINTS:

Mechanized equipment may be restricted when sensitive habitats are adjacent (e.g., stream mouths, tidal flats, marshes, or dunes).

ENVIRONMENTAL EFFECTS:

Intertidal — The equipment is heavy, and required support personnel is extensive. May be detrimental if excessive sediments are removed without replacement. All organisms resident in the beach will be affected, though the need for removal of the oil may be determined to be the best overall alternative.

Subtidal — Release of oil and fine-grained oily sediments to the water during sediment removal activities and tidal flushing of the excavated beach surface.

7. Cold Water Flooding (Deluge)

OBJECTIVE:

To wash surface oil and oil from crevices and rock interstices to water's edge for collection.

DESCRIPTION:

A large diameter header pipe is placed parallel to the shoreline above the oiled area. A flexible perforated header hose is used during deluge of intertidal shorelines to better conform to their profiles. Ambient seawater is pumped through holes in the header pipes and flows down the beach face to the water. On porous beaches, water flows through the substrate pushing loose oil ahead of it (or floats oil to the water's surface) then transports the oil down slope for pickup. Flow is maintained as long as necessary to remove the majority of free oil. Oil is trapped by booms and picked up with a skimmer or other suitable equipment.

APPLICABLE SHORELINE TYPES:

Beaches with sediments coarser than sand, and gently sloping rocky shorelines. Generally not applicable to mud, sand, vegetated, or steep rocky shorelines.

WHEN TO USE:

On heavily oiled shorelines when the oil is still fluid and loosely adhering to the substrate; and where oil has penetrated into cobble or boulder beaches.

This method is frequently used in combination with other washing techniques (low or high pressure, cold or warm water).

BIOLOGICAL CONSTRAINTS:

Not appropriate at creek mouths. Where the lower intertidal contains rich biological communities, flooding should be restricted to tidal stages when the rich zones are under water, to prevent secondary oiling.

ENVIRONMENTAL EFFECTS:

Intertidal — Habitat may be physically disturbed and smothered as sand and gravel components are washed down slope. Organisms may be flushed into lower tidal zones.

Subtidal — Oiled sediment may be transported to shallow subtidal areas, contaminating them and burying benthic organisms.

8 a. Cold Water/Low Pressure Washing

OBJECTIVE:

Remove liquid oil that has adhered to the substrate or man-made structures, pooled on the surface, or become trapped in vegetation.

DESCRIPTION:

Low pressure washing with ambient seawater sprayed with hoses is used to flush oil to the water's edge for pickup. Oil is trapped by booms and picked up with skimmers or sorbents. Can be used with a deluge system on beaches to prevent released oil from re-adhering to the substrate.

APPLICABLE SHORELINE TYPES:

On heavily oiled gravel beaches, rocky coasts, riprap and seawalls where the oil is still fresh and liquid. Also, in marshes and mangroves where free oil is trapped.

WHEN TO USE:

Where adhered oil is still fresh and must be removed due to continued release of oil.

BIOLOGICAL CONSTRAINTS:

May need to restrict use of flushing to certain tidal elevations so that the oil/water effluent does not drain across sensitive low tide habitats. In marshes, use only at high tide and either from boats or the high-tide line to prevent foot traffic in vegetation.

ENVIRONMENTAL EFFECTS:

Intertidal — If containment methods are not sufficient, contamination may be flushed into lower intertidal zone.

Subtidal — Oiled sediment may be transported to shallow subtidal areas, contaminating them and burying benthic organisms.

8 b. Cold Water/High Pressure Washing

OBJECTIVE:

Remove oil that has adhered to hard substrates or man-made structures.

DESCRIPTION:

Similar to low pressure washing except that water pressure is up to 100 psi. High pressure spray will better remove oil that has adhered to rocks. Because water volumes are typically low, may require placement of sorbents directly below treatment areas.

APPLICABLE SHORELINE TYPES:

Rocky shores, riprap, and seawalls. Can be used to flush floating oil or loose oil out of tide pools and between crevices on rocky shores.

WHEN TO USE:

When low pressure washing is not effective at removal of adhered oil, which must be removed due to continued release of oil. When directed water jet can remove oil from hard to reach sites. To remove oil from man-made structures for aesthetic reasons.

BIOLOGICAL CONSTRAINTS:

May need to restrict use of flushing to certain tidal elevations so that the oil/water effluent does not drain across sensitive low tide habitats.

ENVIRONMENTAL EFFECTS:

Intertidal — Removes many organisms on the surface. May drive oil deeper into the substrate if water jet is improperly applied. If containment methods are not sufficient, contamination may be flushed into lower intertidal zone.

Subtidal — Oiled sediment may be transported to shallow subtidal areas, contaminating them and burying benthic organisms.

9. Warm Water/Moderate-to-High Pressure Washing

OBJECTIVE:

Mobilize thick and weathered oil adhered to rock surfaces prior to flushing it to the water's edge for collection.

DESCRIPTION:

Sseawater heated up to 100° is applied at moderate to high pressure to mobilize weathered oil that has adhered to rocks. The warm water may be sufficient to flush the oil down the beach. If not, "deluge" flooding and additional low or high pressure washing can be used to float the oil to the water's edge for pickup. Oil is trapped by booms and picked up with skimmers or sorbents.

APPLICABLE SHORELINE TYPES:

Rocky shores, gravel beaches, riprap, and seawalls that are heavily oiled.

WHEN TO USE:

When the oil has weathered to the point that low pressure washing with cold water is not effective at removal of adhered oil, which must be removed due to continued release of oil. To remove oil from man-made structures for aesthetic reasons.

BIOLOGICAL CONSTRAINTS:

Must restrict use to certain tidal elevations so that the oil/water effluent does not drain across sensitive low tide habitats (damage can result from exposure to oil, oiled sediments, and warm water). Should be restricted adjacent to stream mouths, tide pool communities, and similar rich intertidal communities.

ENVIRONMENTAL EFFECTS:

Intertidal — Can kill or remove most organisms. If containment methods are not sufficient, contamination may be flushed into lower intertidal zones that would otherwise not be oiled.

Subtidal — Oiled sediment may be transported to shallow subtidal areas, contaminating them and burying benthic organisms.

10. Hot Water/High Pressure Washing

OBJECTIVE:

Dislodge trapped and weathered oil from inaccessible locations and surfaces not amenable to mechanical removal.

DESCRIPTION:

Water heaters mounted offshore on barges or small land-based units heat water up to 170°F, which is usually sprayed by hand with high pressure wands. Used without water flooding, this procedure requires immediate use of vacuum (vacuum trucks or super suckers) to remove the oil/water runoff. With a deluge system, the oil is flushed to the water surface for collection with skimmers or sorbents.

APPLICABLE SHORELINE TYPES:

Rocky shores, gravel beaches, riprap, and seawalls that are heavily oiled.

WHEN TO USE:

When the oil has weathered to the point that even warm water at high pressure is not effective at removal of adhered oil, which must be removed due to continued release of oil. To remove oil from man-made structures for aesthetic reasons.

BIOLOGICAL CONSTRAINTS:

Restrict use to certain tidal elevations so that the oil/water effluent does not drain across sensitive low tide habitats (damage can result from exposure to oil, oiled sediments, and hot water). Should be restricted near stream mouths, tide pool communities, etc. Released oil must be recovered to prevent further oiling of adjacent environments.

ENVIRONMENTAL EFFECTS:

Intertidal — All attached organisms in the direct spray zone will be removed or killed, and significant mortality of the lower intertidal communities will result even when used properly. Where the intertidal community is rich, the tradeoff between damage to the intertidal community from the hot water washing versus potential damage from leaving the oil has to be weighed.

Subtidal — Oiled sediment may be transported to shallow subtidal areas, contaminating them and burying benthic organisms.

11. Slurry Sand Blasting

OBJECTIVE:

Remove heavy residual oil from solid substrates.

DESCRIPTION:

Use of sandblasting equipment to remove oil from the substrate. May include recovery of used (oiled) sand in some cases.

APPLICABLE SHORELINE TYPES:

Seawalls and riprap. Equipment can be operated from boat or land.

WHEN TO USE:

When heavy oil residue is remaining on the shoreline, which needs to be cleaned for aesthetic reasons, and even hot water wash is not effective.

BIOLOGICAL CONSTRAINTS:

Not to be used in areas of oyster/clam beds, or areas with high biological abundance on the shoreline directly below or adjacent to the structures.

ENVIRONMENTAL EFFECTS:

Intertidal — Complete destruction of all organisms in the intertidal zone.

Subtidal — Possible smothering of subtidal organisms with sand. When the used sand is not recovered, introduces oiled sediments into the subtidal habitat.

12. Vacuum

OBJECTIVE:

Remove free oil pooled on the substrate or from the water surface in sheltered areas.

DESCRIPTION:

Use of a vacuum unit with a suction head to recover free oil. The equipment can range from small portable units which fill individual 55-gallon drums to large supersuckers that are truck-mounted and can lift large rocks. Can be used with water spray systems to flush the oil towards the suction head.

APPLICABLE SHORELINE TYPES:

Can be used on any shoreline type if accessible. May be mounted offshore on barges, onshore on trucks, or as individual units on boats or ashore at low tide.

WHEN TO USE:

When free, liquid oil is stranded on the shoreline (usually along the high-tide line) or trapped in vegetation which is readily accessible.

BIOLOGICAL CONSTRAINTS:

Special restrictions should be identified for areas where foot traffic and equipment operation should be limited, such as rich intertidal communities. Operations in wetlands are to be very closely monitored, with a site-specific list of restrictions.

ENVIRONMENTAL EFFECTS:

Intertidal — Minimal impacts if used properly and minimal substrate is removed.

Subtidal — None.

Treatment Methods Requiring RRT Approval

Research and development is ongoing for both new and improved oil spill treatment methods. Various chemical and biological degradation techniques are currently being tested for effectiveness and toxicity, and they may be approved for use in certain situations. Methods considered to be of potential use in this area are described below.

13. Cutting Vegetation

OBJECTIVE:

Removal of oiled vegetation to prevent oiling of wildlife.

DESCRIPTION:

Manual cutting of oiled vegetation using weed eater, and removal of cut vegetation with rakes. The cut vegetation is bagged immediately for disposal.

APPLICABLE SHORELINE TYPES:

Marshes composed of emergent, herbaceous vegetation.

WHEN TO USE:

Use when the risk of oiled vegetation contaminating wildlife is greater than the value of the vegetation that is to be cut, and there is no less destructive method to remove or reduce the risk to acceptable levels.

BIOLOGICAL CONSTRAINTS:

Strict monitoring of the operations must be conducted to minimize the degree of root destruction and mixing of oil deeper into the sediments. Access to bird nesting areas should be restricted during nesting season.

ENVIRONMENTAL EFFECTS:

Intertidal — Removal of the vegetation will result in loss of habitat for many animals. Cut areas will have reduced plant growth for up to two years. Along exposed section of shoreline, the vegetation may not regrow, resulting in erosion and permanent loss of the habitat. Trampled areas (which is inevitable) will recover much slower.

Subtidal — Long term impacts would be increased sediment load in the subtidal area as a result of increased erosion in the intertidal area.

14 a. Chemical Oil Stabilization with Elastomizers

OBJECTIVE:

Solidify or gelatinize oil on the water surface or a beach to keep it from spreading or escaping.

DESCRIPTION:

Chemical agent enhancing polymerization of the hydrocarbon molecules applied by semi-liquid spray or as a dry chemical onto the oil in the proper dosage. Depending on the nature and concentration of the polymerizing agent, the oil can be rendered viscoelastic, but still fluid, gelatinous, or semisolid. The primary purpose is to stabilize the oil keeping it from spreading or escaping, causing oiling elsewhere. May reduce the solubility of the light (and more toxic) fractions, by locking them into the polymer. This reduces both air and water exposure. Depending on the beach type and equipment used, recovery may be enhanced. Elastol is an example of an oil stabilizing agent.

APPLICABLE SHORELINE TYPES:

Suitable on shorelines of low permeability where heavy oil has pooled on the surface, except vegetated shorelines.

WHEN TO USE:

When heavy concentrations of liquid oil are on the substrate and adjacent water body, and physical removal can not be completed prior to the next tide so that the oil is likely to move to a more sensitive shoreline type. Should be used in conjunction with booming or other physical containment.

BIOLOGICAL CONSTRAINTS:

Not suitable for vegetated or riprap shore types. Should be avoided when birds or other wildlife that may be more adversely impacted by the congealed oil can not be kept away from the treated shoreline. The congealed oil may stick to vegetation and wildlife, increasing physical damage to both. On riprap the congealed oil may remain in crevices where it may hamper recovery and prolong the release of sheens.

ENVIRONMENTAL EFFECTS:

May enhance the smothering effect of oil on intertidal organisms. Thus, the treatment should be considered only for heavily oiled beaches where smothering effects are already maximal. The congealed oil may stick to vegetation and wildlife increasing physical damage, such as impaired flight in birds or impaired thermoregulation in mammals and birds whose feathers or fur become oiled.

14 b. Chemical Protection of Beaches

OBJECTIVE:

Pretreat shoreline to prevent oil from adhering to the substrate.

DESCRIPTION:

Certain types of water-based chemicals, some of which are similar in composition to dispersants, are applied to beaches in advance of the oil.

APPLICABLE SHORELINE TYPES:

Coarse- and fine-grained sand beaches, seawalls and piers (particularly piers or waterfront facilities that are of historical significance), eroding bluffs, wave-cut platforms, and riprap.

WHEN TO USE:

When oil is projected to impact an applicable shoreline, particularly those which have high recreational or aesthetic value.

BIOLOGICAL CONSTRAINTS:

May not be suitable for nutrient-rich environments, particularly in confined waters. The toxicity of shoreline treatment products is reportedly much less than that of oil, but the toxicity of each product should be evaluated prior to consideration for use.

ENVIRONMENTAL EFFECTS:

The long-term environmental effects of these procedures are unknown. A toxic effect of the chemical can be anticipated. Additionally, the nutrient load to nearshore and interstitial waters may lead to eutrophication. Whether the predicted reduced residence time of the oil on the beach will increase the survival rate for sessile and interstitial organisms is unknown.

14 c. Chemical Cleaning of Beaches

OBJECTIVE:

To increase the efficiency of oil removal from contaminated areas.

DESCRIPTION:

Special formulations which can be characterized as weak dispersants are applied to the substrate, as a presoak and/or flushing solution, to soften weathered or heavy oils to aid in the efficiency of flushing treatment methods. The intent is to be able to lower the temperature and pressure required to mobilize the oil from the substrate.

APPLICABLE SHORELINE TYPES:

On any shoreline where deluge and water flushing procedures are applicable

WHEN TO USE:

When the oil has weathered to the point where it will not flow using warm to hot water. This approach may be most applicable where flushing decreases in effectiveness as the oil weathers.

BIOLOGICAL CONSTRAINTS:

Will required extensive biological testing for toxicity and water quality sampling prior to receiving approval for use. The concern is that the treated oil will be dispersed in the water column, and thus impact water column and subtidal organisms. Field tests will be required to show that use of a beach cleaner does not reduce overall recoverability of the oil. Use may be restricted where suspended sediment concentrations are high, adjacent to wetlands and tidal flats, and near sensitive subtidal resources.

ENVIRONMENTAL EFFECTS:

If more oil is dispersed into the water column, there could be more oil sorbed onto suspended sediments and transfered to subtidal habitats, particularly along sheltered shorelines. Intertidal habitats might survive better, if cooler water temperatures are possible.

15. *In Situ* Burning

OBJECTIVE:

Removal of oil from the shoreline by burning.

DESCRIPTION:

Oil on the shoreline is burned, usually when it is on a combustible substrate such as vegetation, logs, and other debris. Oil can be burned off of nonflammable substrates with the aid of a burn promoter.

APPLICABLE SHORELINE TYPES:

On any shoreline type except tidal flats.

WHEN TO USE:

Early in the spill event, after ensuring that the product is ignitable.

BIOLOGICAL CONSTRAINTS:

Should only be considered for use in the upper intertidal or supratidal zones since destruction of plants and animals from heat and burn promoters will be extensive. This technique is subject to restrictions and permit requirements established by federal, state and local laws. It should not be used to burn PCB's, wastes containing more than 1,000 ppm of halogenated solvents, or other substances regulated by EPA.

ENVIRONMENTAL EFFECTS:

Little is known about the relative effects of burning oiled wetlands compared to other techniques or natural recovery. Burning may cause significant air pollution, which must be considered when weighing the potential benefits and risks of the technique. The combustion products may travel great distances before deposition.

16. Nutrient Enhancement

OBJECTIVE:

To speed the rates of natural microbial degradation of oil by addition of nutrients (specifically nitrogen and phosphorus). Microbial biodegradation is the conversion by microorganisms of dissolved and dispersed hydrocarbons into oxidized products via various enzymatic reactions. Some hydrocarbons are converted to carbon dioxide and cell material, while others are partially oxidized and/or left untouched as a residue.

DESCRIPTION:

Nutrients are applied to the shoreline in one of several methods: soluble inorganic formulations which are dissolved in water and applied as a spray at low tide, requiring frequent applications; slow-release formulations which are applied as a solid to the intertidal zone and designed to slowly dissolve; and oleophilic formulations which adhere to the oil itself, thus they are sprayed directly on the oiled areas.

APPLICABLE SHORELINE TYPES:

Could be used on any shoreline type where safe access is allowed.

WHEN TO USE:

On moderately to heavily oiled shorelines, after other techniques have been used to remove as much oil as possible; on lightly oiled shorelines where other techniques are not effective; and where nutrients are a limiting factor in natural degradation.

BIOLOGICAL CONSTRAINTS:

Not applicable in shallow water, restricted embayments where nutrient overloading may lead to eutrophication, or where toxicity of nutrients, particularly ammonia, is of concern. There must be no risk of oxygen depletion. Use is to be restricted adjacent to stream mouths, tide pools, etc. Contact toxicity of oleophilic formulations may restrict areas of direct application. Bioassay test results should be carefully evaluated, as other chemicals in the formulations could be toxic to aquatic organisms.

ENVIRONMENTAL EFFECTS:

Tests in Alaska showed that interstitial oxygen concentrations did not decrease to such an extent that it limited the supply of oxygen available to the bacteria. The fertilizer applications that increased nutrient concentrations and microbial activity did not harm the nearshore environment. About 99 percent of butoxyethanol, a toxic component of the Inipol formulation, (the fertilizer commonly used in Alaska) degraded to nontoxic compounds within 24 hours after Inipol treatments of cobble shorelines. Researchers also found no evidence that the nutrients released from the treated shorelines stimulated algal blooms.

17. Microbial Addition

OBJECTIVE:

To speed the rates of natural microbial degradation of oil by addition of nutrients **and** microbial products. Microbial biodegradation is the conversion by microorganisms of dissolved and dispersed hydrocarbons into oxidized products via various enzymatic reactions. Some hydrocarbons are converted to carbon dioxide and cell material, while others are partially oxidized and/or left untouched as a residue.

DESCRIPTION:

Formulations containing hydrocarbon-degrading microbes and fertilizers are added to the oiled area. The argument is made that indigenous organisms will be killed by the oil, so new microbial species need to be added to being the process of biodegradation.

APPLICABLE SHORELINE TYPES:

Could be used on any shoreline type where safe access is allowed.

BIOLOGICAL CONSTRAINTS:

Not applicable in shallow water, restricted embayments where nutrient overloading may lead to eutrophication, or where toxicity of nutrients, particularly ammonia, is of concern. There must be no risk of oxygen depletion. Use is to be restricted adjacent to stream mouths, tide pool communities, etc. Bioassay test results should be carefully evaluated, as other chemicals in the formulation could be toxic to aquatic organisms.

ENVIRONMENTAL EFFECTS:

Yet to be evaluated for full-scale field applications.

18. Sediment Reworking

OBJECTIVE:

Rework oiled sediments to break up the oil deposits, increase its surface area, and mix deep subsurface oil layers, which will expose the oil to natural removal processes and enhance the rate of oil degradation.

DESCRIPTION:

Beach sediments are rototilled or otherwise mechanically mixed, with the use of heavy equipment on gravel beaches. The oiled sediments in the upper beach area may also be relocated lower on the beach to enhance natural cleanup during reworking by wave activity (berm relocation).

APPLICABLE SHORELINE TYPES:

Should be used only on beaches exposed to significant wave activity. Tilling-type activities work best on beaches with a significant sand fraction; large equipment can be used to relocate sediments up to boulder size.

WHEN TO USE:

On beaches with significant amounts of subsurface oil, where sediment removal is unfeasible (due to erosion concerns or disposal problems); also where surface oil deposits have started to form pavements or crusts.

BIOLOGICAL CONSTRAINTS:

Could not be used on beaches near shellfish-harvest or fish-spawning areas, or near bird nesting or concentrations areas because of the potential for constant release of oil and oiled sediments. Sediment reworking should be restricted to the upper part of the beach, to prevent disturbance of the biological communities in the lower intertidal area.

ENVIRONMENTAL EFFECTS:

Intertidal — Due to the mixing of oil into sediments, this process could further expose organisms which live below the original layer of oil. Repeated mixing over time could delay the reestablishment of organisms. Relocated sediments would bury and kill organisms. There may be a period of beach unstability as the relocated sediments are redistributed.

Subtidal — There is a potential for release of contaminated sediments to the nearshore subtidal habitats.

19. Shoreline Excavation, Cleansing and Replacement

OBJECTIVE:

To remove and clean oiled sediments, then place them on the beach.

DESCRIPTION:

Oiled sediments are excavated using heavy equipment on the beach at low tide. The sediments are loaded into a container for washing. Cleansing methods include hot water wash or physical agitation with a cleansing solution. After the cleansing process, the rinsed materials are returned to the original area. Cleaning equipment must be placed close to beaches in order to reduce transportation problems.

APPLICABLE SHORELINE TYPES:

Sand- to boulder-sized beaches, depending on the limitations of the cleanup equipment. The beaches must be exposed to wave activity, so that the replaced sediments can be reworked into a natural distribution.

WHEN TO USE:

Applicable on beaches with large amounts of subsurface oil, where permanent removal of sediment is undesired and other cleanup techniques are likely to be ineffective.

BIOLOGICAL CONSTRAINTS:

Excavating equipment must not intrude upon sensitive habitats. Only the upper and supratidal areas should be considered. Generally restricted in spawning areas. There may be site-specific constraints limiting placement of temporary sediment storage piles,. Replaced material must be free of oil and toxic substances. The washing must not change the grain size of the replaced material, either by removal of fines or excessive breakage of friable sediments.

ENVIRONMENTAL EFFECTS:

Intertidal — All resident organisms will be affected, though the need for removal of the oil may be determined to be the best overall solution. Equipment can be heavy, large, and noisy, disrupting wildlife. Transportation to site may entail aircraft, land vehicles, or barges, which contribute to environmental disruption. There may be a period of beach unstability as the replaced sediments are redistributed.

Subtidal — May release oil and fine-grained oily sediments into the water during excavation. This is a concern due to tidal flushing of beach sediments and exposed excavations.

Other Techniques

Beach Cleaners

During the *Exxon Valdez* oil spill, Exxon spent considerable time and money developing an effective and low-toxicity chemical cleaner which would speed the removal of weathered oil from the beaches of Prince William Sound. Their approach was to use the chemical as a presoak to be applied prior to water washing, to soften the oil and increase removal efficiences at lower temperatures. Exxon conducted a detailed screening program of commercially available products to find the product which would remove the most oil but also had low dispersive properties. It was not acceptable to have the oil removed by dispersion to the nearshore water column.

Exxon eventually developed their own product, Corexit 9580, and conducted extensive bioassays and field effectiveness tests in Alaska (Fiocco et al., 1991). This product was shown to have very low toxicity, in both laboratory bioassays and in situ testing of run-off water from full-scale field testing sites. The main concern about the product was recoverability of the released oil; during tests, it appeared that the released oil was dispersed more into the nearshore water than at control sites. Beach cleaners might be appropriate for cleaning man-made structures, such as seawalls and riprap, assuming that the oil can be recovered. Since recovery was still an issue in the most extensive testing yet conducted on beach cleaners, their use without further testing is unlikely.

Elastol

Elastol is a commercial product composed of polyisobutylene in a white powder form. Polyisobutylene is a non-toxic constituent found in foodstuffs. Issues on application of Elastol for oil spill response include:

- Elastol increases the resistance of spilled oil to being pulled apart or broken up (viscoelasticity) by temporarily altering hydrocarbon molecular shape.
- The treated oil must be pulled; pushing it makes it lose its elastic properties.
- The effects of Elastol are reversible.
- Application:

  -Traditionally applied as a powder from conventional dusters

  -Recently applied as a slurry mixture with a 15 percent calcium stearate coating with water. Has consistency of "cream of wheat."
- Application rates vary with oil type, with lower rates for heavier oils:

  -Light oil spills: 1000-2000 ppm

  -Bunker C spills: 100-200 ppm
- Lower application rates are recommended because they allow the oil to revert back to its original condition more readily and at lower costs.
- Starts working in 15-60 minutes, with faster times for lighter oils.
- Elastol particles float, due to the coating. Dissolution occurs after mixing with hydrocarbon liquids.

- Toxicity:

  -Very low toxicity (see below)

  -Lowers toxicity of oil by "binding" soluble toxic fractions into the "Elastoil" mixture.

Toxicant	*Artemia salina* 48 hour LD_{50} (ppm)	*Fundulus heteroclitus* 96 hour LD_{50} (ppm)
Elastol	>18,000	>18,000
No. 2 fuel oil	600	3,200
1:10 mixture (Elastol:No. 2 fuel oil)	>3,200	>18,000

Seagrasses showed no toxic effects

CONCERNS:

- Non-uniform application results in "clumping" of oil/Elastol mixture into highly viscous, sticky masses. Can be countered with sawdust. But behavior of this sticky mass when the mixture strands on the shoreline is of concern.
- Potential problems for birds, fur-bearing mammals, marshes, mangroves, etc. Do not know difference in impacts to oiled versus "Elastoiled" animals.
- Recovery is best with a specially designed drum skimmer, which must be transported to the site, causing delays.

PHYSICAL EFFECTS (based on laboratory, tank, and field tests)

- There was no simple correlation between oil type and effectiveness.
- Elastol increased these physical properties of oil:

  -Viscoelasticity

  -Slick thickness (only at application rates greater than 1 percent).

- Elastol decreased the extent of oil slick spreading.
- Elastol did not affect these oil properties:

  -Evaporation rate

  -Flash point

  -Weathering rates
- Emulsion formation tendency tests have produced mixed results; formation of emulsion decreases the effectiveness of Elastol.
- Elastol reduced the effectiveness of chemical dispersants applied after Elastol use by up to a factor of 10.
- Elastol reduced natural dispersion by up to three orders of magnitude (so it could be used to reduce oil levels in the water column in shallow water conditions).

Observations from a test of Elastol on a heavy black oil spill in New York harbor on 26 December 1988, as recorded by Ed Levine, the NOAA SSC, are:

> "Approximately 25 minutes after application of Elastol B to the oil a thickening of product was observable. At this time the vacuum hose was used to begin removing the product from the creek. Due to the amount of floating debris included in the oil, a problem was encountered with clogging of the nozzle by this debris, however, at this time it was not significantly greater than non-treated oil.
>
> ..."After approximately one hour from the original application of Elastol, we changed the removal sites to the lee of the floating dock. The product encountered here was quite thick and exhibited stretch lines as the vacuum nozzle was applied to it. The oil could be observed migrating towards the vacuum source. The nozzel was then moved to an area of untreated oil. A marked difference in the thickness and behavior of the oil could be noted. This oil was approximately the consistency of water, while the treated oil was like thick molasses. Also noted was the increased recovery of water with the untreated oil, as opposed to the treated oil, which removed mostly oil."

Although Elastol has had very little field testing, it appears to work as advertised. Recovery is still a problem, as is the case for any type of spilled hydrocarbon.

Bioremediation

Bioremediation should be considered in the context of the entire suite of spill treatment technologies, including the option of no treatment. Only when there is a clear reason for using bioremediation should its potential use be pursued. Bioremediation is considered promising because it enhances natural biodegradation, which occurs in most areas where oil is spilled. In fact, in areas that are lightly oiled, natural, unassisted biodegradation may be the best "treatment." The key question to ask in these circumstances is, *Can bioremediation offer an improvement over natural levels of biodegradation?* It will probably be necessary to conduct a small-scale test of the proposed bioremediation technique to answer this question.

Bioremediation is most promising as a long-term treatment, so there should be no hurry to attempt to rush through an evaluation procedure during the first few hours after a spill occurs. Alternate techniques exist for immediate spill response that have been tried and tested more extensively. If a need for longer-term shoreline treatments is identified, then bioremediation can still be considered effectively days or weeks after the spill event.

Before becoming involved in the details of protocols and planning considerations, it may be useful to step back for a moment and evaluate the three main types of bioremediation currently being considered for oil spill response: fertilizer application, microbial additions, and open-water applications.

Fertilizer

Use of fertilizer for accelerating biodegradation on oiled shorelines is the most well-documented and well-researched type of bioremediation. Many aspects of the technology are promising, particularly its potential use in areas that would be affected detrimentally by more intrusive physical treatments. However, the variable results from field tests confirm that this is not yet an off-the-shelf technique that can be applied to oiled shorelines with the expectation of success in all cases. Perhaps the most enlightening aspect of many of the studies of fertilizer use is that unassisted biodegradation does occur at high rates in many locations, and that the no-treatment option perhaps should be considered more frequently.

Bioremediation with fertilizer is complicated, because natural biodegradation rates vary considerably (from days to months) depending on the environment and the oil in question. Temperature is an important consideration, as is the amount of organic matter and nutrients, salinity, and oxygen. This means that caution must be exercised when applying results from one area to an application in another environment. Like most other treatment technologies, decisions will probably need to be made on a case-by-case basis. What works in one situation may not be effective or may be inappropriate for another situation. Monitoring should be conducted to verify the effectiveness of the application, and to document any adverse impacts.

Fertilizer may be most appropriately considered in the following situations, if it is determined that nutrients may be limiting:

Sheltered shorelines that are heavily oiled, when techniques for physical removal of the oil are impractical or infeasible, or have already been attempted;

Shorelines with substantial subsurface oil that may degrade very slowly. (In this case, increased oxygen may need to be supplied to the subsurface);

Sensitive environments, especially marshes and wetlands that will be impacted adversely by other cleanup methods.

Fertilizer will be inappropriate in circumstances such as the following:

Environments that are already nutrient-rich (nutrients are not limiting in these cases—see Prall's Island discussion). This can be tested by measuring background nutrient levels before beginning a bioremediation experiment.

For short term, immediate response actions. Usually, physical techniques will first be used to remove as much oil as is feasible, and then fertilizer may be considered for longer-term, follow-up treatment.

Microbial products

Use of microbial products for treatment of open environments is still an experimental technology. Few microbial products can show increased degradation over use of fertilizer alone when tested under standardized laboratory conditions. No data that currently exist show that microbes increase biodegradation in open environments when they are compared with use of fertilizer alone. The same environmental constraints that affect fertilizer treatments also apply to microbial products, with the added uncertainty of whether the supplemental microbes will survive and become active in a foreign environment. Microbial products would theoretically be useful in environments that are lacking indigenous microbes, but this has not been the case at most environments studied in the context of marine oil spills.

At this time, the use of microbial products in open environments for treatment of oiled shorelines should be considered for experimental testing purposes only. Further, until the National Environmental Technology Applications Corporation (NETAC) protocols are in place, a considerable burden of evaluating unknown products rests with the spill responder. The decision on whether to use microbial products should be made only after careful evaluation of the products available, and after evaluating data on their toxicity and effectiveness. Without reliable data on the effectiveness and potential toxicity of a microbial product, it will be impossible to make an informed decision on its application in the marine environment.

Open-water. Open-water bioremediation is presently the least promising bioremediation technology. Since bioremediation is a long-term process which does not begin to significantly degrade oil until a period of several days to several weeks after exposure to oil, it is questionable whether it could work on an oil slick. Much of the initial loss of oil in slicks is through evaporation, and it is doubtful that biodegradation is actively occurring during this time period (since the volatile fractions of the oil are toxic to bacteria). Thus, a bioremediation product, whether fertilizer or microbial, would have to become active during a window of time after the volatile fractions of the oil have evaporated and before the oil has formed weathered compounds that are more resistant to biodegradation. The bioremediation product must also stick to the oil and remain at the surface-water interface for an extended period of time.

The unknown questions about open-water bioremediation will be difficult to answer due to the logistical problems of conducting research on oil slicks. The long history of attempting to document the effectiveness of dispersants also applies to open-water bioremediation techniques. Controlled field studies under real oil spill conditions are extremely difficult to conduct, and research on intentionally spilled oil even more so. Since open-water use of bioremediation is highly experimental, and many substantial questions still need to be answered, this technology should presently not be considered in any situation other than a research context.

Monitoring recommendations

There is no single measure that will accurately measure effectiveness or toxicity of a bioremediation application. Most of the larger bioremediation monitoring programs that have been undertaken have used a combination of the techniques discussed, depending on their specific concerns and objectives (DuPont 1991; Prince et al. 1990; Pritchard et al. 1991). For example, the Alaska studies measured several different parameters for toxicity, water quality and effectiveness (See Table 5-4). As a minimum, a monitoring plan at a bioremediation field test or application should include at least the following endpoints:

1) To measure effectiveness, track changes in indicator hydrocarbon compounds by gas chromatography/mass spectroscopy (GC/MS). Samples should be collected at least at the beginning and end of the sampling period at control and treated sites.

2) Conduct toxicity testing using bioassays to determine acute and/or chronic toxicity to aquatic organisms (see NETAC protocols for examples.) Bioassays should include sediment bioassays if the bioremediation chemicals are likely to lodge in sediments. Testing should include test sites and control sites.

3) Monitor environmental impacts to aquatic habitats through chemical analysis of sediments or water for potentially toxic compounds (such as heavy metals) that may be part of a bioremediation product. Samples should be collected at the beginning and end of the sampling period at control and treated sites.

Biodegradation versus bioremediation

Biodegradation is the natural process whereby bacteria or other microorganisms alter and break down organic molecules into other substances, such as fatty acids and carbon dioxide. *Bioremediation* is the act of adding fertilizers or other materials to contaminated environments, such as oil spill sites, to accelerate the natural biodegradation process (U.S. Congress 1991). Bioremediation is also used in terrestrial and other applications, including sewage treatment, terrestrial oil spills, and experimentally for hazardous wastes.

Three main types of bioremediation technologies are currently being developed or applied for treatment of oil spills: addition of fertilizer to oiled shorelines, addition of microbial products to oiled shorelines, and addition of fertilizer and/or microbial products to open water oil slicks. Since all of these technologies attempt to accelerate biodegradation, this report presents a short summary of the processes of biodegradation of oil, a discussion of some of the potential uses of this technology, including specific instances where bioremediation has been applied at oil spills, and presents guidelines for evaluation and monitoring of bioremediation applications.

How does biodegradation work?

Biodegradation is one of the main ways in which spilled oil is weathered. It occurs in most environments, but at varying rates, depending on localized environmental conditions and on the composition of the oil (for example, heavier oils are more resistant to biodegradation than lighter oils) (Atlas 1975). Among the many environmental factors that will affect biodegradation rates, oxygen, nutrients, and temperature are probably the most important (Atlas 1981; DeFlaun and Mayer 1983).

Simply adding oil to an environment will stimulate growth of indigenous microbes, since the oil provides increased amounts of carbon, the microbes' food source (Lee and Levy 1991). Several researchers have documented a lag period before indigenous microbial communities begin to degrade oil (Fusey and Oudot 1984; NOAA 1980). This may be due to the fact that oil is initially toxic to microbial organisms, and the most toxic fractions must be weathered before microbes can grow, a time period of several days to several weeks (Lee and Levy 1989b).

The primary processes of microbial degradation are aerobic (requiring oxygen), though anaerobic degradation may occur at very low rates. Low-energy, sheltered environments probably have the lowest rates of biodegradation, especially in subsurface sediments. Oil in anaerobic sediments in marshes or other environments may degrade very little, with oil persisting in some cases for several years (Delaune et al. 1980; Atlas 1981; Lee and Levy 1991). High-energy environments usually show rapid biodegradation, in part because of physical weathering, but also because wave action supplies oxygen and nutrients to the microbial communities, facilitating biodegradation (Lee and Levy 1989a). See the OTA report for a thorough discussion of the chemical processes of biodegradation (U.S. Congress 1991).

Microbial populations that undergo rapid growth in the presence of spilled oil may become limited by inadequate amounts of nutrients, such as nitrogen and/or phosphorus. Field tests on biodegradation of a waxy crude oil (Terra Nova crude) in sandy beaches found that fertilizer addition was effective in accelerating biodegradation in areas that were heavily oiled, but less so in areas that were lightly oiled (little acceleration was measured in these areas). This was due to the fact that unassisted biodegradation occurred very rapidly in the lightly oiled areas (Lee and Levy 1991). Nutrients are less likely to be limiting to microbial population growth in the water column for degradation of suspended oil particles, than for oil on shorelines or concentrated in oil slicks (Atlas 1981).

At extremely high salinities, biodegradation is inhibited (Ward and Brock 1978), but this is not likely to be a problem in the normal range of salinities usually encountered in marine and coastal environments (Lee and Levy 1989a).

Types of bioremediation

Nutrient addition (fertilizer)

The theory behind bioremediation by nutrient addition is simple: microbes already living on an impacted shoreline have a sudden new source of food—carbon compounds in the spilled oil. After the initial toxicity of the oil wears off (usually by evaporation of the volatile compounds) and after indigenous species of hydrocarbon-degrading microbes become acclimated, they begin to "eat" the oil, and their population grows. At this point, the sudden increase in numbers of microbes may deplete existing supplies of nutrients (specifically nitrogen and/or phosphorus) and this may limit further growth of the microbial population. With added nutrients, the microbial population can continue to increase, and degrade oil at a faster overall rate, than without the supplemental nutrients.

Numerous laboratory studies on fertilizer enhancement of oil biodegradation by naturally occurring microbes have concluded that fertilizer enhancement has potential as a treatment technique for oiled shorelines (NOAA 1978; Atlas 1981; Lee and Levy 1987; Lee and Levy 1989a). Field experiments have also been conducted, but these have not always corroborated the laboratory results (Fusey and Oudot 1984; Lee and Levy 1991). Results from field tests are less clear, in part because it is difficult to actually measure biodegradation outside of the laboratory. It is also difficult to determine statistical differences in biodegradation rates between control areas and fertilized areas in the field due to environmental variability and high spatial variability in the distribution of oil in sediments of impacted areas. It also appears that biodegradation rates can vary substantially between environments, probably due to environmental factors such as temperature or other very localized conditions (Prince et al. 1990; DuPont 1991; Pritchard et al. 1991).

The potential advantages of any bioremediation technique must be balanced against possible detrimental environmental effects, including introduction of contaminants, toxicity to aquatic organisms, and physical impacts. Some fertilizer products, whose primary use is in a terrestrial setting, may contain trace metals as micro-nutrients (e.g., copper or mercury) that would be introduced into an aquatic environment with potentially much more significant toxicological effects (Mearns 1991). Others may produce by-products such as ammonia and/or nitrates that are toxic to aquatic organisms at certain concentrations (U.S. EPA 1989). Intertidal organisms that are directly exposed during application of the undiluted fertilizer solution may be adversely impacted. In addition, physical disturbance from the application process and from monitoring will have some impacts on the shoreline, especially in sensitive environments such as marshes.

Fertilizer use is still experimental in marine environments; therefore, any application should include a monitoring program to determine whether the desired objectives have been met, and whether any adverse impacts have been minimized to acceptable levels of risk. Following are summaries of different types of fertilizers and application techniques that have been used in bioremediation experiments or applications.

Types of fertilizers

Fertilizer addition can involve a variety of application techniques and numerous commercial fertilizer products, some that have been developed specifically for use on oil spills, and others that have been adapted from agricultural or domestic use. These products can be grouped into three basic categories: soluble inorganic fertilizers, oleophilic fertilizers, and slow release fertilizers. Each is discussed in more detail below.

Soluble inorganic fertilizers. Inorganic fertilizers include a wide variety of water-soluble lawn or agricultural fertilizers that can be mixed with seawater and sprayed on shorelines. These fertilizers can be formulated with different ratios of nitrogen and phosphorus and usually include small quantities of trace elements. Some advantages of inorganic fertilizers are that they are readily available, inexpensive, and usually consist of compounds with well known properties. However, since these fertilizers are water-soluble, they may be washed off the shoreline by tidal action, requiring frequent, repeated applications. There may also be some direct toxicity (i. e. burning) to plants or animals in the intertidal zone that are directly impacted during the application process.

Oleophilic fertilizers. Oleophilic fertilizers were developed to solve the problem of fertilizers washing off rocks or beaches. Oleophilic (literally, "oil-loving") fertilizers are chemically "sticky" and adhere to oil on rocks or other substrates. In theory, these fertilizers are designed to remain at the oil-water interface and are therefore readily accessible to oil-degrading microbes. In Prince

William Sound, Alaska, the oleophilic fertilizer Inipol EAP 22 was applied extensively to oiled shorelines and was investigated in several monitoring studies.

Inipol contains oleic acid (a source of carbon), urea (a source of nitrogen), tri(laureth-4)-phosphate (a surfactant), and 2-butoxy-ethanol (another surfactant) (Pritchard et al. 1991). Since addition of oil alone will stimulate bacterial growth, the presence of oleic acid in the fertilizer complicates evaluation of the effectiveness of oleophilic fertilizers such as Inipol. Do these products appear to work better because the microbes are eating the carbon in the fertilizer instead of the spilled oil? Lee and Levy (1989b) concluded that addition of an oleophilic fertilizer to a low-energy beach contaminated with crude oil was ineffective as a bioremediation agent because the microbes were preferentially eating the organic components of the fertilizer instead of the oil.

Several scientists have argued that Inipol appears to be effective because it is acting primarily as a chemical surfactant rather than as a bioremediation agent. Surfactants, such as the ones in Inipol, are found in cleaning agents and dispersants. Inipol contains approximately 10% 2-butoxy ethanol, a common ingredient in household cleaning agents, and also one of the ingredients in the dispersant Corexit 9527 (Exxon 1989a; Keyser 1991; Exxon 1989b). Critics have argued that some of the dramatic visual effects noted during field observations using oleophilic fertilizers are a result of the surfactant properties of the fertilizer, rather than from stimulated biodegradation.

Several components of Inipol are toxic to humans and other organisms at certain concentrations. These include 2-butoxy-ethanol, and urea, which produces ammonia when it comes in contact with water. 2-butoxy-ethanol is toxic to mammals, especially in the first 48 hours after application. Effects on humans include eye and skin irritation, and damaged blood cells with repeated exposure. This requires that special safety precautions be taken for workers who handle Inipol, such as wearing clothing (rubber boots and aprons) or respirators if exposure to fumes or dust is likely (Exxon 1989b).

Slow-release fertilizers . Slow-release fertilizers are designed to release quantities of fertilizer over a longer period of time, and to remain in the area where they are applied. They include various brands of fertilizer mixes, packaged in dissolvable capsules or briquettes. These formulations, in theory, release small quantities of nutrients slowly over a period of time. While briquettes may move about on the beaches with tidal action, granules will usually lodge among pebbles and cobbles and remain in the intertidal zone. In this way, the dosage of fertilizer is controlled at low levels and release of fertilizer to the subsurface may be facilitated as granules work their way down into sediments.

Several brands of slow-release fertilizers were tested in Prince William Sound in 1989 by EPA, and one granule product, Customblen™, was subsequently applied extensively on shorelines (Pritchard et al. 1991). Customblen contains nutrients (ammonium nitrate, calcium phosphate, and ammonium phosphates) encased in a polymerized vegetable oil (Prince et al. 1990). Assuming that the pellets remain in the intertidal zone, Customblen does not need to be applied as frequently as liquid fertilizers. Some possible disadvantages include the possibility that pellets may wash away or lodge at the high tide zone on high-energy beaches. Concentrations of pellets higher than the recommended application could collect in one location (such as a tidal pool) and create concentrations of ammonia that could be toxic to aquatic organisms.

Fertilizer applications

Exxon Valdez
March 1989 - 1991

In March 1989, approximately 350 miles of shoreline in Prince William Sound were oiled with North Slope crude oil from the *Exxon Valdez* spill (Pritchard and Costa 1991). In the early summer, following preliminary results from a bioremediation test program conducted by the EPA's Alaska Oil Spill Bioremediation Project, the Alaska RRT approved the use of fertilizer as bioremediation to treat oiled shorelines. A number of constraints were placed on the use of fertilizer, including a restriction to areas that were well-flushed, and a prohibition from applying fertilizer in sensitive areas such as near anadromous fish streams. The decision on whether to apply bioremediation to specific shorelines was made on a segment-by-segment basis. In 1990, continued use of bioremediation as a shoreline treatment was approved with the requirement that a monitoring program be conducted to evaluate the effectiveness and safety of the bioremediation applications (U.S. Congress 1991; Prince et al. 1990; Pritchard et al. 1991).

The studies conducted in 1989 and 1990 in Prince William Sound were comprehensive and investigated the effectiveness of different types of fertilizers at several sites, including several test and control plots. Monitoring also included sampling and analysis of various water quality parameters and toxicity testing (Table 5-4; Prince et al. 1990; Pritchard et al. 1991).

Effectiveness: Though several articles published about the bioremediation studies in Prince William Sound have claimed dramatic and successful results (Pritchard and Costa 1991), a careful evaluation of the data leads to a more cautious conclusion (Kellogg 1991). Though studies conducted in both years were carefully designed and included control plots, all of the data had high levels of variability, making it difficult to determine overall differences between fertilized plots and control plots.

1989 Studies: In 1989, one of two treated test plots in Passage Cove (treated with water-soluble fertilizer applied with sprinklers) showed statistically significant differences in oil residue weight when compared with the control site. The second test site (treated with Inipol and Customblen) did not show a significant difference in oil residue weight compared with the control site. (Measures of oil residue weight varied at all sites by up to two orders of magnitude.) Microbial counts showed no significant differences in numbers of microbes between treated and control plots. However, significant differences were found between numbers of bacteria at oiled sites versus unoiled sites, demonstrating that the presence of oil by itself will stimulate microbial growth (Pritchard et al. 1991).

At a second study conducted in 1989 at Snug Harbor, measurements of oil residue weight over time were highly variable among all plots, including control plots. (Values ranged over an order of magnitude.) Decreasing trends in oil residue weight were found at all plots, including the control plot. No data showing statistical comparisons were presented, but there did not appear to be strong differences between control and treated plots in oil residue weight loss over time. Gas chromatograph analyses showed degradation rates that appeared to be higher at treated sites (Pritchard et al. 1990; Pritchard et al. 1991).

<u>1990 Studies</u>: The studies conducted in 1990 encountered the same problem as those in 1989 with highly variable distributions of oil in sediments. This resulted in such high levels of variability in measures of oil residue weight, that detecting differences by quantitative analysis was deemed impossible without greatly increased numbers of samples (approximately an order of magnitude greater; Prince et al. 1990). Analyses using gas chromatography that tracked specific compounds showed qualitatively that biodegradation was occurring, but differences between control and treated sites were difficult to detect. Overall results of effectiveness were inconclusive.

There are several reasons why the results from both years were somewhat inconclusive: background rates of biodegradation were found to be "surprisingly high" at control plots; second, there could be strong differences in local environmental conditions that either favor or inhibit biodegradation at each individual site. Further, a process of declining returns would be expected in 1990, since most of the remaining oil was weathered, and thus more

TABLE 5-4. Bioremediation Case Histories

	Treatment History				Monitoring		
Incident	Location/Substrate	Type of Oil	Type of Bioremediation	Products	Days Monitored	Endpoints Measured	Application Effective?
Exxon Valdez	Prince William Sound, Alaska shorelines	Prudhoe Bay crude	fertilizer	Inipol Customblen	1989: 99 days 1990: 55 days	oil residue weight GC/MS respirometry microbial counts acute toxicity water quality chlorophyll	yes, partially
Prall's Island	Arthur Kill, New Jersey gravel beach	fuel oil	fertilizer	Customblen	92 days	TPH* GC/MS microbial counts water quality	no
Apex Barges	Galveston Bay, Texas marsh	partially refined (catalytic feed stock)	microbial	Alpha BioSea Miracle-Gro	11 days	TPH percent oil in mousse acute toxicity	inconclusive
Seal Beach	Southern California marsh	crude	microbial	INOC 8162 Miracle-Gro	35 days	GC/MS phenanthrene mineralization respirometry microbial counts	no
Mega Borg	Gulf of Mexico open water	Angolan crude	microbial	Alpha BioSea	7 hours	percent oil in mousse acute toxicity	inconclusive

(Parris and Albrecht 1990; Prince et al. 1990; Texas General Land Office 1990; Exxon 1991; Goodbred 1991; Mearns 1991; Pritchard 1991; Pritchard et al. 1991; U.S. EPA 1991)

*total petroleum hydrocarbons

resistant to biodegradation. These studies can be interpreted as showing that *some fertilized sites* showed trends with increased rates of biodegradation, with stronger evidence of effectiveness in the first year.

Toxicity: Bioassays conducted using oyster and mussel larvae showed some acute toxicity, while bioassays using mysids showed no acute effects. These were conducted with water samples from beaches after treatment with both Inipol and Customblen (Sanders and Gray 1989; Prince et al. 1990; Pritchard et al. 1991). No chronic toxicity tests were conducted, nor were analyses made for sediment toxicity or direct toxicity of Inipol to intertidal organisms.

Prall's Island, New Jersey
June 1990 - December 1990

In January 1990, a pipeline at the Exxon Bayway refinery in Linden, New Jersey broke. Fuel oil was spilled into the Arthur Kill waterway, contaminating a beach on the Prall's Island bird sanctuary. Most of the oil was removed by physical means, but these efforts were halted in March 1990, partly to avoid impacts to migrating birds using the area. Exxon Research and Engineering received permission to conduct a bioremediation experiment on part of the beach with remaining oil (DuPont 1991).

The experiment used a slow-release fertilizer (Customblen) placed in two shallow trenches dug in the intertidal zone. In an attempt to get around the usual high variability in distribution of oil on the beach, bags of beach substrate containing known concentrations of oil were buried in each test plot. Samples from each of these bags were measured for total petroleum hydrocarbons (TPH) at the end of the experiment to compare rates of biodegradation (DuPont 1991). Microbial counts made on beach samples taken before fertilization showed high background levels of microbes in the test area. Background levels of nitrogen and phosphorus were also high when measured prior to the beginning of the experiment (DuPont 1991).

Effectiveness: The overall results showed no clear trends of increased rates of biodegradation from fertilized plots. This was, in part, due to the high variability in the levels of TPH measured in soils and sampling bags from all plots, including the control plot. Some problems were experienced with possible cross-contamination of the control plot (nutrients leaching from the treated plots into the control plot), and this may have obscured any differences between them. The fact that high numbers of microbes were measured in the substrate before the fertilizer treatment began may be an indication that background levels of biodegradation were naturally high. This is not surprising since Prall's Island has been chronically impacted by oil spills in the past, and indigenous microbial populations may be well adapted to the presence of hydrocarbons. Also, the previously existing high levels of nitrogen and phosphorus would suggest that nutrients may not be a limiting factor in this system.

Toxicity: Though no bioassays were conducted as part of this experiment, levels of ammonia in offshore and interstitial waters were generally below levels that would be toxic to aquatic organisms (EPA 1989). Levels of dissolved oxygen in offshore waters and in the interstitial waters of the test plots were monitored throughout the experiment. Ammonia levels were highest in the lower intertidal areas of the treated plots, ranging from 4-10 ppm, while levels at the control plot ranged from 0-2 ppm.

Microbial products

Adding microbes to contaminated areas, also known as "seeding," is conducted to enhance biodegradation of an oil-impacted area with selected strains of microbes that are known to be capable of degrading hydrocarbons. However, the effectiveness of adding microbes to the environment to enhance biodegradation is not well supported in the scientific literature (Atlas 1981). In fact, studies indicate that addition of microbes to an open environment probably does not increase biodegradation because "foreign" strains of bacteria, out-competed by indigenous species, disappear quickly from the microbial community (Lee and Levy 1989b).
No strain of bacteria, whether indigenous or from a product application, is likely to degrade oil actively until after the most toxic components of the oil have evaporated (Lee and Levy 1987). Therefore, claims of "instant success" from microbial products should be regarded with skepticism. The argument is made that indigenous organisms will be killed by the oil, so new microbial species need to be added to begin the process of biodegradation. In fact, studies have found that most areas of

the world contain some microbes that are capable of degrading oil, and that these usually grow rapidly when they have acclimated to an oil spill (Lee and Levy 1989a).

Currently, no genetically engineered microorganisms are being considered for use in bioremediation (U.S. Congress 1991).

To date, few objective scientific studies have been conducted that have tested microbial products currently on the market. The most comprehensive was conducted by Venosa et al. (1991a, 1991b) of the EPA Office of Research and Development in Cincinnati. In brief, the lab study compared the biodegradation of weathered Prudhoe Bay crude oil using individual applications of 11 microbial products and fertilizer alone at 15˚C. Two products showed a statistically significant increase in biodegradation over fertilizer. However, these products performed as well with sterilized (dead microbes) as with live microbes. Both of the two highest performers were then tested in a controlled, replicated field test in Alaska. In the field, no significant difference in oil residue weight or total resolvable alkanes could be detected among the control plots, the fertilized plots, or the plots treated with microbial products. (See also the discussion below on the results from Seal Beach.)

Most microbial products either contain or recommend use of some type of fertilizer, so the concerns about potential toxicity discussed in the section on fertilizer should be considered here as well. In addition, concerns have been raised about microbial products that contain strains of bacteria that are potential human or animal pathogens. Other chemicals that are possibly part of microbial products (such as binders or surfactants), could also be toxic to aquatic organisms. Therefore, bioassays or other toxicity testing should be conducted as part of monitoring.

Microbial applications

Apex Barges, Texas
August 1990

A collision between three Apex barges and the tanker *Shnoussa* occurred on July 28, 1990, spilling approximately 700,000 gallons of a partially refined oil into Galveston Bay. Shorelines and marshes along the northern shore of the Bay were contaminated by the oil approximately one week after the initial spill. The Texas Water Commission received approval from the Region 6 RRT to conduct a trial application of a microbial bioremediation product (Alpha BioSea) to a contaminated marsh (Mearns 1991). RRT approval was given under certain guidelines, including that the application be done only in areas where mechanical recovery of oil was not feasible, and that a scientifically sound monitoring program be conducted. The Texas Water Commission carried out the monitoring program with consultation from NOAA and EPA representatives who also acted as on-site observers.

On August 5 the pre-mixed solution containing the microbial product and a nutrient mix was applied to the marsh by a high-pressure hose from a small boat. Samples of water and sediment were collected both before treatment and at approximately 24, 48, and 96 hours after the treatment. Additional samples were collected at 9,10, and 11 days after the intitial application. All samples were sent to an EPA laboratory for analysis.

<u>Effectiveness</u>: No noticeable differences between treated and untreated plots could be discerned in samples collected 48 hours after treatment. Results from EPA-analyzed samples are not yet available, but samples analyzed by NOAA using gas chromatography/mass spectroscopy showed no apparent changes in the relative abundances of specific compounds in the oil before and after treatment. Many problems experienced in the monitoring program prevented the collection of useful information and made the results of the experiment unclear. These problems included poor control over application of the product, disturbance of the test areas by livestock and numerous human activities, and a too-short period of sample collection after the application (Table 5-4; Mearns 1991).

These results are not surprising for several reasons. First, since Galveston Bay is chronically impacted by oil spills, one could expect that indigenous populations of bacteria would be well adapted for hydrocarbon degradation. Therefore, it is questionable whether additional microbes were needed in this environment. Second, the short period of the monitoring could probably not have measured any acceleration in biodegradation rates if it had in fact occurred, since biodegradation usually does not begin until several days or weeks after a spill. Third, there is no way to separate any effects due to the microbial product from effects due to the fertilizer. Fourth, the feed stock oil was already in a degraded form (Mearns 1991). The Alpha BioSea product should have been tested first in the laboratory to determine if it could accelerate biodegradation when compared with fertilizer alone.

Toxicity: Water samples collected after the application were tested and found to be acutely toxic to mysids. Additional concerns about potential toxic effects of trace metals in the nutrient mix were raised by Mearns (1991).

Seal Beach, California
November 1990

A well blowout offshore of Seal Beach, California occurred on October 31, 1990, releasing approximately 400 gallons of crude oil into the atmosphere, resulting in the oiling of approximately two to three acres of marsh grasses in the Seal Beach National Wildlife Refuge (U.S. Department of the Interior 1990; U.S. EPA 1991b).

Bioremediation treatment with a microbial product plus fertilizer was undertaken one week after the blowout, followed by an application of fertilizer alone two weeks later. Treatment consisted of hand spraying of grass blades with a combination of a microbial product used in sewage treatment plants (INOC 8162) and a commercial fertilizer (Miracle Gro 30-6-6). Samples of unoiled, oiled, and treated, and oiled grass were collected and analyzed by the EPA Environmental Research Laboratory in Gulf Breeze, Florida (U.S. EPA 1991b).

Effectiveness: The results of a number of laboratory tests performed on samples taken from the marsh showed no differences between oiled and treated grasses and oiled grasses with no treatment. Measures of degradation included most probable number counts of bacteria and ^{14}C mineralization, a relative measure of biodegradation rate. In addition, a laboratory study was performed by EPA to compare the ability of the INOC product to degrade Prudhoe Bay crude oil with uninoculated (nutrient only) controls. After 7 and 16 days of incubation, little or no difference was found in the amount of four indicator compounds in the flask containing the product compared with the control flask. Thus, the microbial product was not effective in accelerating biodegradation of oil under controlled laboratory conditions (U.S. EPA 1991b).

Toxicity: The U.S. Fish and Wildlife Service has collected samples of plants and invertebrates and intends to analyze these tissues for presence of hydrocarbon compounds (Goodbred 1991). These analyses have not yet been performed, and no other toxicity testing has been reported to date.

Open-water bioremediation

Studies from the early 1970s in laboratory and simulated large tank situations have investigated the use of addition of fertilizer on open water oil slicks (Atlas and Bartha 1973). However, to date, no studies have evaluated use of bioremediation (microbial or fertilizer) in an open ocean situation. From a research viewpoint, it is still unknown whether bioremediation would be effective on a recently spilled, open-water oil slick.

Biodegradation in the water is thought to occur at the water surface (Lee and Levy 1989a). Therefore, any product or nutrient added would need to stay at this interface and follow the oil slick as it moves. For bioremediation to be successful on open water, the nutrients or products would have to remain with the oil slick for the time it takes microbes to become acclimated to the oil and to begin biodegrading.

As in shoreline applications, the question has been raised, *Do bioremediation products applied on open water actually act as dispersants or surfactants, redistributing oil into the water column?* If this is the case, should these products then be considered dispersants and not bioremediation agents? (If these products are considered dispersants, they are covered by separate regulations.)

The same concerns for potential toxicity that have been discussed for use of fertilizers and microbes on shorelines also apply to open-water applications. The dilution factor is likely to be much greater on open water, however, and this is likely to lessen the risk from direct toxic effects. As with dispersants, monitoring will present very real difficulties, including formidable logistics for applications, measurements or observations, and the difficulty of collecting samples that will provide meaningful data.

Open-water applications

Mega Borg, Texas
June 1990

The *Mega Borg* spill in 1990 is the only known application of a microbial product to an open-water oil slick in the United States. The *Mega Borg* supertanker was transferring its cargo of Angolan crude oil at a location approximately 60 nautical miles off the coast from Galveston, Texas, when an explosion caused a fire and subsequent release of oil. Oil was released continuously for nine days. The Region 6 RRT gave approval to the Texas Water Commission to conduct an experimental, open-water application of a microbial product to the slick. The microbial product was applied from a Coast Guard vessel twice, 6 and 9 days after the initial explosion. Sampling was conducted from a Texas A&M University research vessel and included samples of surface water and subsurface samples from 1 and 9 m depths. Three of these samples were sent to the EPA Gulf Breeze Lab for toxicity testing (Parrish and Albrecht 1990; Research Planning 1991).

Several problems were encountered during the experiment, including interference by skimmers working in the same area where the first application was made, and logistical problems with the sampling vessel, resulting in no sample collection during the first application. A dispersant test was also conducted during this spill (Payne et al. 1991), causing further competition for logistics platforms.

<u>Effectiveness</u>: Results from the percentage of oil found in samples of mousse from surface water were inconclusive since no differences could be detected between samples collected before and after the bioremediation application. As stated by the Texas General Land Office report: "The high variability in these samples... demonstrates the difficulty of obtaining comparative and consistently representative samples in the open ocean, and the unequal mixing of the oil on the water surface." (Texas General Land Office 1990 p.10).

The Texas General Land Office relied heavily on visual observations made several hours after the application to evaluate the experiment (Texas General Land Office

1990). Since it is unlikely that microbial activity could have begun this quickly after application (see background discussion), it is likely that the observed visual changes in the appearance of the slick were caused by physical processes such as dispersion. This experiment demonstrates both the difficulties inherent in attempts to conduct open-water experiments and the inconclusive results that can be expected from open-water bioremediation.

Toxicity: Results of the EPA Gulf Breeze Lab's acute (96 hour) bioassays performed on silversides and mysids showed no acute effects, but the researchers questioned whether the samples were actually collected in an area impacted by the oil slick, since no trace of oil was found in the samples (Parrish and Albrecht 1990). The bioremediation product was not directly tested for toxicity.

Evaluation of bioremediation technologies

The EPA Interim Guidelines provide guidance for establishing protocols for the use of bioremediation in spill response, and include several sections relating to evaluation of bioremediation techniques and products. The Guidelines offer a comprehensive discussion of feasibility assessment, screening of bioremediation agents, logistics, and monitoring. A useful guide for screening of bioremediation proposals or plans are the seven points of concern listed in section 1-2 of the guidelines (EPA 1991a.)

For screening specific bioremediation products, a four-tiered protocol is being developed by the National Environmental Technology Applications Corporation (NETAC) for standardized testing and evaluation of bioremediation products. (These protocols are in appendix B of the Interim Guidelines). The NETAC protocols include preliminary screening, laboratory testing (including toxicity testing), microcosm testing, and field testing. When in place, bioremediation products will be required to pass through these tiers in order to be approved for consideration at oil spills. These protocols are still in the development stage and are expected to be finalized in approximately one year.

Since bioremediation is not yet a fully developed, off-the-shelf technology, a preliminary evaluation should be undertaken prior to the development of spill response plans, such as those suggested in the Interim Guidelines. This evaluation should determine whether certain bioremediation techniques have reached a stage where they are ready to be considered for use in spill response, or for experimental testing, or not at all.

Following the NETAC approach using sequential evaluation tiers, a similar process can be applied to the bioremediation techniques discussed in this report, considering them as technologies in various stages of development. These can be looked at through four "evaluation tiers" as follows:

1) Is the technique supported in theoretical research?
2) Has the technique been tested in the laboratory?
3) Has the technique undergone small-scale field testing?
4) Has the technique been applied in an open environment on a large scale with monitoring?

Rationale

The rationale for these tiers is as follows: a technique should first be shown to be effective in the lab, where conditions can be controlled. This should represent an ideal case for proving, through scientific methods, that a technique works as intended. However, a technique which is proven to be effective in the lab may not be equally effective under field conditions, which are much more variable and unpredictable. Certainly, if the performance of a product is poor in the lab, then more research and refinement of the product needs to be done before it should be considered for field application. Only when a technique has been shown to work in lab and field tests should it be considered for a larger-scale application. If a technique cannot be shown to work in controlled lab and field tests, it is more appropriately considered in a research context than in a response context.

Evaluation tiers

1) The first tier is the theoretical research and development of the idea and theory behind the technology. At the present time, all of the three proposed applications for bioremediation at marine oil spills have some basis in research theory, though this is more strongly supported for some applications (fertilizer) than for others (microbial seeding and open-water bioremediation).

2) The second tier is testing the technology and proving that it works effectively under controlled laboratory conditions. Fertilizer has been repeatedly shown to be effective in laboratory flask tests, while only a few microbial products have been shown to be effective in lab tests (conducted by laboratories other than those of the manufacturing company). Open-water applications have not been successfully tested under controlled conditions.

3) The third tier is a small-scale field test in an open environment. Both fertilizer and microbial bioremediation have undergone field testing, with mixed results. Results from two field tests with microbial products did not show increased degradation over fertilizer (U.S. EPA 1991b; Venosa et al. 1991b). Field tests using fertilizer alone have been shown to increase biodegradation in some plots, but not with overall statistical significance (Prince et al. 1990; DuPont 1991; Pritchard et al. 1991). Results from the open-water bioremediation application at the *Mega Borg* yielded no conclusive results about effectiveness of open-water applications (Texas General Land Office 1990).

4) The fourth tier is equivalent to a response action, i.e., large-scale field application with monitoring. In normal circumstances, a technique would have successfully passed through the first three tiers before any considerations were made for large scale applications. However, due to the unplanned nature of oil spill response in the past, many techniques were tried before previous evaluation tiers had been completed. For example, fertilizer was applied on a large scale as part of treatment of shorelines in Prince William Sound in conjunction with smaller-scale field tests. Neither microbial applications to shorelines nor open-water bioremediation have been made in other than in small, experimental circumstances.

   In several cases, decision makers and oil spill responders have been asked to consider large-scale bioremediation applications in open environments without having any information about prior scientific research or laboratory testing of the particular technique. Such attempts to rush into use of a potentially untested or invalid bioremediation technique are unfortunate in that they usually result in confusion about effectiveness, and risk an unsuccessful application of bioremediation. Worse, such attempts could divert resources away from other potentially more effective cleanup treatments, and could potentially add negative impacts to environments already affected by an oil spill.

Monitoring

Since all forms of bioremediation are still experimental in open environments, and because local environmental conditions will affect how a particular technique works, a monitoring program should be set up with any bioremediation application to determine whether the technique is working as intended. The monitoring process may be more costly than the application itself, and this should be weighed with other factors when considering whether to use bioremediation as part of a spill response.

To be effective, monitoring should be well planned and include carefully selected control sites. Replicate sampling of all test and control plots should be included when possible. Important factors to consider when setting up a monitoring program include the questions to be asked, the endpoints to be measured for answering these questions, the type of samples to be collected, where the samples will be collected, and the time frame for sampling. (See EPA Interim Guidelines for further discussions on monitoring).

Questions to be addressed by monitoring

One of the most basic parts of a monitoring program is to define clearly which questions or concerns the program is being designed to answer. Nearly always these will include, *Is this technique effective?* Or, *Did the technique accelerate the rate of biodegradation of oil in the area of concern relative to an untreated control?* In this case, a measure of the biodegradation rate is necessary, so that the rates in the treated area can be compared with rates in a similar, untreated area. Another major concern is, *Are there detrimental effects from the treatment?* Usually the potential for toxicity to aquatic organisms will be a concern for resource agencies and, in some cases, other potential environmental effects such as eutrophication or physical impacts from sampling. Additional questions may be posed, depending on the situation. All such questions must be formulated in advance so that the monitoring program can be designed to gather the data necessary for addressing the issues of concern. After the basic questions are identified, endpoints can be chosen and a sampling plan developed.

Sampling endpoints

Endpoints are a specific definition of what is meant by a general term like *effective*. What, exactly, will be used to determine whether a technique is effective? The endpoints to be measured should be selected in advance to avoid confusion when interpreting monitoring results. In general, it is better to avoid reliance on qualitative measures such as "visual differences," which are very difficult to interpret, and may vary depending on the observer.

Some specific endpoints are discussed below for measuring...

1) biodegradation
2) toxicity
3) other environmental effects

1) Biodegradation

Measuring biodegradation is not a simple task, and it has become a central part of monitoring for effectiveness of bioremediation techniques. Most of the measures that have been used in bioremediation experiments involve laboratory tests performed on samples collected in the field. These are relative measures, but they are the best that are available at the present time.

a. Visual observations: Visual observations can indicate a number of processes, such as dispersion, movement of oil from the surface, oil attaching to substrate in a product (such as cornstarch, an additive in some microbial products), photo-oxidation (a physical process), or other weathering processes. There is no way to determine what a visual change represents without corroboration from more specific measurements. Visual observations are also very difficult to standardize between observers. (See discussion of Apex Barges, *Mega Borg* and Alaska incidents).

b. Total petroleum hydrocarbons: A commonly used method for measuring the overall reduction of oil at a bioremediation test site is to take sediment samples before bioremediation and again some time after application and measure these for total petroleum hydrocarbons (TPH). (This is also referred to as oil residue weight).

Consistently, studies measuring TPH have been unable to detect differences between sites because of high spatial variability in the distribution of oil in sediments (Prince et al. 1990). Therefore, TPH has in most cases, not proved useful for determining effectiveness of bioremediation.

The difference between starting and ending concentrations of TPH measures not only loss of hydrocarbons from biodegradation, but also losses from physical weathering. Further, TPH does not provide information on the toxicity of the remaining components of the oil. Despite these drawbacks, TPH is still proposed as a measure of effectiveness in bioremediation experiments because it provides a gross indicator of the amount of remaining oil, and it is less costly than other, more detailed chemical analyses such as gas chromatography.

c. Gas chromatography: Many experts in the field recommend the use of gas chromatography and mass spectroscopy to characterize the biodegradation process, since the use of measures of total residue (such as TPH) are many times not adequately informative (Walker et al. 1976; Prince et al. 1990). Gas chromatography can trace patterns of specific compounds that are only broken down by microbial processes, thus tracking biodegradation separately from physical weathering. Examples of indicator compounds that are used in this way are hopane compounds and the ratio of C18 to phytane. Gas chromatography will also indicate what percentage of the oil is made up of the more toxic components. Gas chromatography is, however, more expensive than other, more gross chemical measures, and this will limit the number of samples that can be analyzed.

d. Microbial counts: Methods such as most probable number counts (MPN) estimate the number of microbial cells in a sediment sample. These types of counts are accurate only within an order of magnitude, and are not a measure of microbial activity, but only of the number of microbial bodies. (Some percentage of microbes are usually in a dormant state.) Microbial counts can be used as a rough indication of the microbial population in an area, and to determine whether the microbial population has grown in response to a bioremediation application.

e. Mineralization: A widely used measure of microbial activity is ^{14}C mineralization. This is a relative index of bacterial activity with specific substrates, not an absolute measure total oil degradation (Lee and Levy 1989a). Sediment samples are collected from test plots and brought to the laboratory where the biodegradation rates of the microbes in the sample are measured. Studies using mineralization include the two Alaska experiments (Prince et al. 1990; Pritchard et al. 1991) and Seal Beach (U.S. EPA 1991b). In these cases, mineralization rates were quite variable between samples and between sites, but some trends could be discerned, showing higher rates at some treated sites compared with rates at control sites.

2) Toxicity

Toxicity can be monitored by collecting water samples and analyzing for specific compounds or by conducting bioassays. Many bioremediation monitoring programs have measured water samples for concentrations of ammonia or other chemicals of concern (Alaska studies, Prall's Island). Acute bioassays will give a good indication of immediate toxic effects to aquatic organisms. (Acute tests were performed in Alaska and at the Apex Barges incident). Chronic bioassays are important for assessing long-term, non-lethal effects, and may be indicated in long-term treatments or treatments involving repeated applications.

3) Other environmental effects:
Other possible environmental effects that may be of concern include eutrophication in offshore waters or other detrimental effects on water quality. Eutrophication is not likely to be a problem in well-flushed systems, or over a short time period in sheltered environments. Studies in Prince William Sound and at Prall's Island found no elevated levels of nutrients offshore of treated beaches (DuPont 1991; Pritchard et al. 1991). Eutrophication can be monitored by measuring levels of nutrients and dissolved oxygen in offshore waters before and after treatment applications.

Sampling design

An appropriate sampling design helps ensure that the data collected provide answers to the initial questions posed in the monitoring plan. Sampling may be simple or very complex, but it should correspond to the objectives of the monitoring. Sample design includes consideration of control sites, number of samples, locations of sample collection, timing of sampling, and sample handling and analysis. It is more useful to take a few carefully thought-out samples than to take numerous samples without proper planning and follow-through.

Controls

Sampling controls are an essential part of any scientific experiment. Since bioremediation is an acceleration of biodegradation over the background rate, it is necessary to know the background rate for comparison. Without a comparison value, there is no way to tell whether bioremediation was successful, or whether it was a superfluous exercise. Since the state of the art of bioremediation is still evolving, any open-environment application should be considered experimental, and should require a control. Data collected without controls will be of limited utility for assessing effectiveness.

In some cases, recognized standards or criteria exist that can be used as comparison values for measuring toxicity or other adverse environmental impacts. Values such as EPA ambient water quality criteria, or sediment toxicity standards can serve this function.

Usually a control will consist of a sample plot that is as similar to the test plot as possible, but far enough away so that it will not be influenced by the treatment. At the Prall's Island experiment, the control site was located adjacent to treated sites on both sides, and it is likely that nutrients from the treated sites leached into the control site, thereby contaminating it.

Ideally, the control plot should be treated identically to the treated plot, except for the actual treatment. For instance, if the treatment involves sprinkling the area with fertilizer mixed with seawater, the control should be sprinkled with seawater without fertilizer. A different type of control was exemplified by the use of bags of sediment with known quantities of oil planted in test sites at Prall's Island. This was a promising idea that attempted to address the problem of high spatial variability of oil distribution in sediments. Unfortunately, in this case it did not yield the desired result (less variability in the data). But the concept could be experimented with and refined further.

<u>How many samples?</u> The number of samples to be collected depends on the question being asked, on the kind of data analysis to be done, and on the resources available. A larger number of samples often allows greater power for statistical analysis, but will be more costly. One strategy is to collect a large number of samples in the field and then to analyze only a subset of the samples collected, depending on the initial results. A small number of samples will provide an indication of the processes occurring, but may not be representative of the entire study area.

<u>Where to sample?</u> Where samples should be collected is tied closely to the number of samples and to the sample analysis. Often, the sample area is divided into sections based on conditions such as oiling (e.g., heavily oiled, lightly oiled, unoiled), or substrate type (e.g. cobble, gravel). A representative sample is then collected from each section. The Alaska studies in 1989 conducted tests at two sites, one heavily oiled and one moderately oiled, then sub-divided one site into plots of cobble and gravel substrate (Pritchard et al. 1991).

When possible, avoid taking samples in areas with outside influences that may confound the results, such as areas near outfalls or freshwater streams. Samples taken in the middle of the plot will usually be more representative than samples taken along the edge. Another method is to lay a grid pattern over a map of the test area and choose samples randomly in each designated area.

Timing of sample collection: The appropriate time frame for collecting samples will depend on the questions being addressed. For example, for monitoring the effectiveness of bioremediation on a beach, samples could be collected before application, soon after application, and at several subsequent intervals of several weeks' duration. In contrast, if monitoring for toxicity, the time scale will likely be much shorter, probably immediately after application and at several subsequent times hours after application (4 hours, 8 hours, etc.). The Galveston Bay monitoring program was an example of a time frame that was probably too short for monitoring biodegradation, though it was appropriate for monitoring toxicity. (See Table 5-4 for comparison of monitoring time frames).

Analysis and protocol for handling samples: The laboratory designated to conduct the analysis should be consulted prior to sampling to ensure that samples are handled appropriately.

Monitoring recommendations

There is no single measure that will accurately measure effectiveness or toxicity of a bioremediation application. Most of the larger bioremediation monitoring programs that have been undertaken have used a combination of the techniques discussed, depending on their specific concerns and objectives (DuPont 1991; Prince et al. 1990; Pritchard et al. 1991). For example, the Alaska studies measured several different parameters for toxicity, water quality and effectiveness (See Table 5-4). As a minimum, a monitoring plan at a bioremediation field test or application should include at least the following endpoints:

1) To measure effectiveness, track changes in indicator hydrocarbon compounds by gas chromatography/mass spectroscopy (GC/MS). Samples should be collected at least at the beginning and end of the sampling period at control and treated sites.

2) Conduct toxicity testing using bioassays to determine acute and/or chronic toxicity to aquatic organisms (see NETAC protocols for examples.) Bioassays should include sediment bioassays if the bioremediation chemicals are likely to lodge in sediments. Testing should include test sites and control sites.

3) Monitor environmental impacts to aquatic habitats through chemical analysis of sediments or water for potentially toxic compounds (such as heavy metals) that may be part of a bioremediation product. Samples

should be collected at the beginning and end of the sampling period at control and treated sites.

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6 Field Methods for Oil-Spill Response

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Chapter 6.
Field Methods for Oil-Spill Response

Introduction

Oil spills, by their very nature, create a sense of urgency and chaos with respect to the collection of meaningful field data. To do so requires discipline and a systematic approach. In this chapter, we present a number of methods that have proved useful to us in gathering data at dozens of oil spills. It is important that the methods used are relatively simple and that the same methodology is followed throughout the spill response. In this discussion, emphasis is placed on gathering data relevant to making clean-up decisions and recommendations for protection of resources at risk.

Reconnaissance Studies of Large Areas

Hayes et al. (1973) developed a systematic sampling program for rapidly classifying large sections of coastline in Alaska. This method, called the Zonal Method, has been modified somewhat for application in the assessment of the initial extent and persistence of oiling at major oil spills.

This modified zonal method is described in detail below:

1) Collection and study of available literature, aerial photographs, maps, and charts occurs as soon as possible. Maps on the scale of 1:24,000 are available from the U.S. Geological Survey (USGS) for most sections of the United States. These are most useful for delineating oil distribution, as well as for determining coastal geomorphology. Charts of all U.S. coastal areas may be obtained from NOAA and are usually readily accessible from marinas in the impacted area. Aerial photographs are more difficult to obtain rapidly and have to be ordered through either the federal or state government.

2) An aerial overflight of the entire area is conducted during low tide to observe maximum exposure of the intertidal area. An aerial survey allows an extremely rapid assessment of the entire spill site and is especially useful in determining the relationship between regional geomorphology and oil distribution. Inflight observations are recorded both verbally on tape and photographically with a hand-held 35-mm camera (for details, see discussion on photography which follows), or a videocamera (preferably both). The flight is conducted at 500-1,500 ft. altitudes, although higher or lower altitudes

can be taken if desired and local flight regulations permit it. Either a helicopter or fixed-wing (high-wing) aircraft may be used.

3) Specific areas are selected for detailed study, based on the aerial survey, local maps, and oil distribution. The sampling interval depends on the variety of coastal types, as well as logistical and financial considerations. Areas selected are representative of the local geomorphology, habitat type, and oil distribution.

4) Two types of stations are set up: (a) visual inspections stations and (b) zonal stations.

   Visual inspection stations. - These sites are surveyed rapidly to determine coastal type, aerial extent of oil coverage, and the thickness and depth of buried oil layers as observed in small trenches dug across the beachface. The value of these studies, usually initiated to establish habitat protection and clean-up priorities, is greatly enhanced if the field team includes an experienced field ecologist. Ideally, the team should include: (a) a coastal geomorphologist; (b) a coastal ecologist; and (c) a field technician well-versed in chemical sampling techniques. Photographs are taken to document oil distribution, biological impact, and coastal morphology. Notes taken are recorded in a field notebook and verbally on tape.

   Zonal stations. - The oil distribution, sediment type, biota, and geomorphology at these stations are studied in much greater detail than at the visual inspection stations. The following tasks are performed at each station:

   a) A topographic profile is run from the back beach to seaward of the low water line, using a horizon-leveling technique which will be demonstrated in the field. Two permanent stakes are established, a back stake (BS) located well back of the normal storm wave erosion zone, and a front stake (FS) just behind the spring high-tide swash line. The profile is run within two hours of low tide in microtidal (TR = 0-2 m) or mesotidal (TR = 2-4 m) areas. In macrotidal areas (TR = >4 m), the upper intertidal zone is exposed for a greater amount of time, and profiles can be run within three hours of low tide. Examples of both blank and completed profile data sheets used for these surveys are given at the end of this chapter. At each horizontal-distance reading on oiled beaches (usually a maximum of 3 m), it is necessary to record the change in elevation, the percent oil coverage (estimated along that section of beach) and the oil thickness (as read off the profile rod). Comments noted on the profile sheet should include sediment type, geomorphic variations (berm crest, cusp horn, etc.), oil appearance, and biological information (species and abundance). The high-tide swash line and water level should be indicated. Stake heights are recorded in case erosion or deposition occurs that far up the beach between repetitive profiles.

b) Sediment samples are taken at three equidistant sites along the profile. Sampling sites are usually marked before running the profile, so they can be appropriately located on the profile sheet. If possible, an unoiled sample is taken for textural analysis; otherwise, the oil will have to be removed by a tedious chemical process. In some cases, surface oil should be scraped away. The sediment sample should consist of 100-200 g of sediment taken to a depth of 10-15 cm. If the sediment is coarse gravel, a photograph (with scale) is taken of the site and the grain size is estimated using the comparator chart given in Figure 3-14. Sediment size may also be measured from the projected image after the photograph is developed. If time and costs demand, one sediment sample taken at the mid beachface will suffice. The remaining sampling sites should be described in detail as to sediment size and sorting.

   Oiled sediment samples of both surface and subsurface oil contamination are usually collected. In gravel areas, surface samples may be individual clasts placed into the sample jars for analysis, usually for detailed characterization and analysis of weathering trends. In non-gravel areas, the surface samples come from the top 2 cm of sediment. Subsurface samples are collected from discreet intervals, frequently from the bottom of the oiled sediments in trenches dug in the beach. Other intervals are collected as appropriate. No samples are composited; the samples are usually "grab" samples. All samples are numbered sequentially, with surface samples denoted 'A'; subsurface samples denoted 'B'; and so on. Samples are collected with clean scoops and placed in pre-cleaned glass jars with teflon-lined caps.

c) Visible effects of the oil on biological communities are observed and recorded. The location and distribution of oiled (and clean) sessile organisms are photographed and described in order to determine temporal changes in the population. In each case, a 15-cm or 30-cm scale is placed in the picture in order to determine the area of the surface photographed (e.g., 0.8 m^2) for mortality counts. In most cases, more detailed biological surveys augment and expand upon the findings of the reconnaissance surveys.

d) Trenches are dug along the profile line to discern the distribution of buried oil. The thickness, depth of burial, and general consistency of the oil are described. Photographs are taken of all the trenches. On some sand beaches, it is useful to dig a trench across the entire beachface. Data concerning the extent of buried oil are necessary to accurately determine the quantity of oil incorporated within the intertidal zone. Samples are usually taken of the oiled layers within the trench to determine quantity and composition of the oil.

e) A hand-drawn sketch is made of the zone surrounding the profile line to force the geomorphologist to carefully observe all aspects of the site. Both a blank and filled-in examples of field sketch forms are given in the materials at the end of this chapter. On the sketch, the following should be noted:

1) Beach morphology
2) Profile line
3) Sample locations
4) Oil distribution
5) Trench locations
6) Depth of buried oil
7) Critical epifauna and flora
8) Cleanup operations if in progress (or effects if completed)
9) All samples taken
10) All photographs taken

5) Sand samples are analyzed for size characteristics by standard sieving techniques (Folk, 1968) or by a rapid sediment analyzer. If these instruments are not readily available or time is critical, grain size can be estimated using a grain-size comparator which illustrates premeasured size classes for direct comparison to the sample (using a hand lens).

6) The coast is categorized into its geomorphological components and oil distribution is superimposed onto base maps. Oil distribution may be categorized as follows*:

Very light	-	<5 percent coverage (of the intertidal zone)
Light coverage	-	25 percent coverage
Moderate coverage	-	25-65 percent coverage
Heavy coverage	-	>65 percent coverage

---

* These boundaries and terms (i.e., very light, light, moderate, heavy) are frequently in dispute at a spill. The measures need to be standardized.

7) Follow-up surveys and overflights are necessary to determine longer-term oil retention, cleanup effectiveness, and geomorphic changes.

The following equipment is required to carry out this type of reconnaissance survey:

Cameras (including video cameras)

Two profile rods (1.5 m long marked at 2 cm intervals)

Day pack, which contains: a) plastic sediment sample bags, b) photo scales, c) hand level, d) compass, e) sand grain-size comparator, f) hand lens, g) measuring tape (30 m, marked in cm), h) film, i) Write-in-the-Rain field notebook, j) orange surveyor's marking tape and orange spray paint, and (k) a tool for scraping sides of trenches (e.g., plasterer's trowel).

Plastic, box-type clip board, which contains: a) profile sheets, b) sketch sheets, c) gravel grain-size comparator, d) percentage estimate chart, e) roundness chart, f) plastic one-foot rule (marked in cm), g) extra lead pencils (plus erasers), h) magic markers, and i) sample-labeling tape.

Four-foot stakes to mark survey sites, two per site—2 x 2 wood stake for front stake and metal fence post for back stake.

Shovels and sledge hammers.

Photography

Professional quality photographs are absolutely essential during spill response. Photographs convey ideas and information much more effectively than written words alone. In transmitting data, a photograph should assist—not confuse and irritate—the audience. Video-taping equipment is a necessity for documenting spill occurrence and distribution. Following are some helpful hints to avoid some of the common pitfalls made by scientists photographing an oil spill site.

1) Film is cheap!! Don't be afraid to take pictures. The expenses associated with a scientific oil spill response often run into hundreds of thousands of dollars.

2) Cameras. The field camera must be durable, preferably lightweight, and have a through-the-lens light meter. Many of the new 35-mm, single-lens, reflex compact cameras by Nikon, Minolta, Olympus (etc.) fulfill these requirements.

3) Lens. A 50-mm or 55-mm lens gives the viewer the most realistic picture of the object. A low F-stop (1.4-1.8) is necessary to be able to take pictures under varying light conditions. A UV filter should be used to protect the lens. The use of a polarizing filter during good light conditions eliminates much of the glare coming off the water (used primarily during overflights, unless the sun is extremely bright).

4) Beach Shots. At least three photographs should be taken of the beach: (1) up and (2) down the coast and (3) directly perpendicular to the beach. At zonal stations, additional photographs should include those of the profile line, trenches, and all aspects of oil distribution and biological effects. A person in the photograph is useful for discerning scale and depth of field.

5) A Straight Horizon. One of the most common problems for the beginner coastal photographer in taking pictures is a crooked horizon—make sure it is straight! In order to present a balanced photograph, it should be composed of approximately one-third sky (sometimes less) and two-thirds land.

6) Shutter Speed. The slower the shutter speed, the greater the depth of field. We most often use 1/125 of a second or 1/60 of a second during darker conditions.

7) Film Type. We have found that Kodachrome-64 gives us good pictures both on the beach and during overflights. It is a wide-latitude film capable of absorbing exposure errors, gives natural colors, and does not appear grainy. Good quality black-and-white prints can also be made. In addition to K-64, we also take some high-speed Ektachrome (ASA 400) in the field in case of poor light conditions. Film is constantly being upgraded. We recommend that you experiment with other types of film. But, don't use it at a critical spill until you have tried it on a beach somewhere.

8) <u>Bracketing</u>. Take the shots you feel are most important as your light meter reads, and then two others at ±1/2 F-stop. This will be a better guarantee of getting the correct exposure. Always check your light meter against other cameras. Change the battery regularly.

9) <u>Shooting into the Sun</u>. On a bright day (looking toward the sun), your camera will read at a closed aperture. This will result in an underexposure or a dark photograph of the beach. In order to get the correct exposure, take the light reading out of the sun's glare or open up the aperture 1/2 to 1 F-stop.

10) <u>Close-Up Photographs</u>. For determining the biological and geological impact of an oil spill, the close-up photograph is most useful. In all cases, an object of well-known size <u>must</u> be placed in the photograph for scale. Preferably, the scale should be marked in centimeters and placed in the lower right-hand corner of the photograph. The 15-cm scale that you will receive at the course works very well. NEVER place the scale in the center of the photograph. The camera should be held parallel to the surface to be photographed to prevent out-of-focus edges.

11) <u>Aerial Photographs</u>. Aerial photographs are usually down-stopped 1/2-1 F-stop. The exact setting varies greatly from camera to camera and should be tested beforehand. If you are not sure about your camera, shoot straight on. Shutter speed should be set at 1/250 or faster, if possible. Don't steady the camera by leaning against the plane (vibrations!). Photographs should be taken through an open window or door, if possible; if not, at least make sure the window is clean. Again, be careful to avoid crooked horizons. Also, beware of reflections—wear dark shirts to minimize reflection.

Guidelines for Detailed Shoreline Contamination Surveys

At any spill of a significant size, a repetitive, detailed systematic survey of the extent and degree of shoreline contamination is needed for:

1) Assessment of the need for shoreline cleanup.

2) Documentation of spatial oil distribution over time.

3) Internally consistent historical record of stranded oil patterns for use by other scientific surveys on intertidal and nearshore subtidal impacts.

Survey teams must use uniform terminology for describing shoreline oil. If all survey teams are using the same terms and definitions, then there is a greater likelihood of consistency in oil reports. Therefore, the attached shoreline survey forms were developed for recording field observations on the extent and degree of shoreline contamination. These forms are similar to those used at the *Exxon Valdez* spill, the development of which was spearheaded by Ed Owens and other Woodward Clyde, Inc. scientists under contract with Exxon. The forms given in this manual were customized by J. Michel of RPI to the spill conditions and coastal geomorphology of the Arabian Gulf. Each geographic area impacted by a spill will require that minor modifications be made to these forms in order for them to conform to the local geomorphological, ecological, and oiling conditions.

During a shoreline survey, the entire shoreline should be systematically inventoried. If this is not possible, then selected sites representative of a larger area should be surveyed in more detail. Individual sites should be on the order of several hundred meters long. These representative sites can be monitored over time for tracking the changes in oil distribution. The temporal changes in the stranded oil will provide important information on the need and priorities for shoreline cleanup.

There are four different pages to the survey forms. The Shoreline Oil Terminology/Codes sheet lists all the terms to be used to describe the oil, sediments, and other features, on the forms and sketches. Training of the survey teams should include review of photographs and videos of each type of oil and extensive discussion of the range of types likely to be encountered in the field. The sheet should be taped to a clipboard for ready referral in the field.

The Shoreline Survey Form is used to record the observations at each site in a systematic manner. For each type of oil on the shoreline, the team would enter in check marks for the distribution and location by tidal zone. For example, the dimensions of individual asphalt pavements and tar mats would be recorded; each tar mat or pavement would be numbered and shown on the attached site sketch. Any trenches dug to observe subsurface oil would also be numbered and located on the attached sketch. For each trench, the form allows ready recording of the depth of the trench, its location in the intertidal zone, a description of the subsurface oil, the depth interval of the subsurface oil, the depth of the water table, and the nature of the subsurface sediments. With this type of information, repeat surveys can be made to measure the change in both surface and subsurface oil over time.

Two types of sketches are recommended. The site sketch should cover the entire shoreline section being surveyed, in plan view. The coastal geomorphology and oil distribution should be shown. The location and number of tar mats, asphalt pavements, trenches, etc. are delineated. The sketch is very important; it allows others to get a sense of the site and interpret the other data on the forms. Because of the scale of most sites, no photograph can capture the site, except for low-altitude aerial photography. The sketch also forces the team to make systematic and more complete observations. Attached is an example site sketch. Any symbology used on the sketch should be added to the legend. For example, different patterns can be used to show substrate types. The codes should be used as abbreviations on the sketch.

A second type of sketch form is for recording trench descriptions. These descriptions are very important in recording the nature of buried oil, which may pose longer-term problems with oil persistence and beach erosion. The Trench Description Form allows for quick recording of the sediments and oiling with depth. This information will be critical in assessment of the potential volumes of sediment removal, if needed. Trench descriptions from the 1991 *Exxon Valdez* surveys are included as examples. The presence and extent of buried oil has both operational and scientific applications.

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PROFILE ______________ LOCATION ______________________ DATE ______________

RECORDERS ______________ PHOTOGRAPHS ______________________ TIME ______________

TIDE STAGE ______________ WEATHER ______________ WIND SPEED ______________ DIRECTION ______________

PROFILE ANGLE ______________ BREAKER HT. ______________ BREAKER ANGLE ______________ BREAKER TYPE ______________

SEDIMENT TYPE ______________________

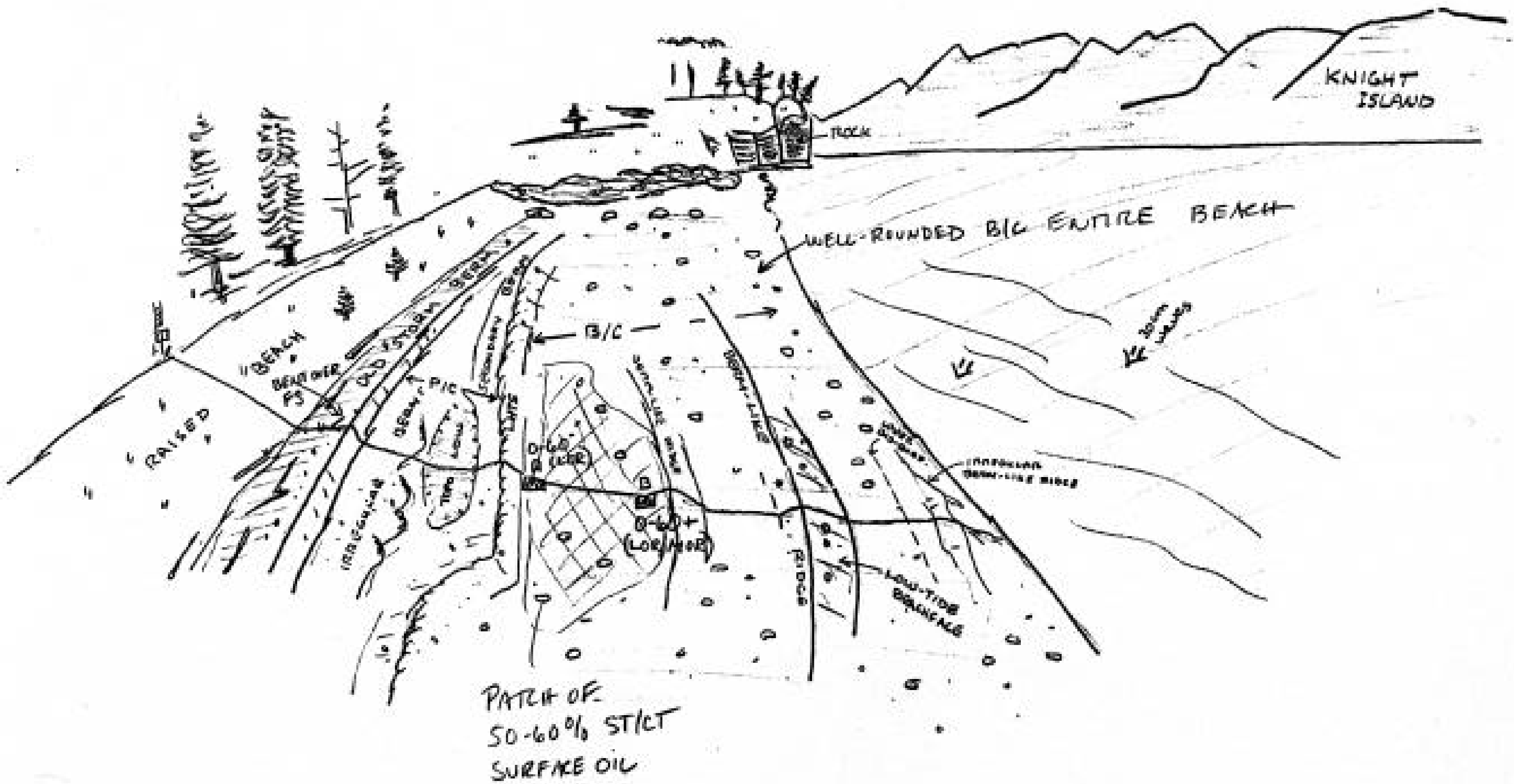
PROFILE N-15 | LOCATION LATOUCHE ISLAND, PWS, AK | DATE 28 AUGUST 1991

RECORDERS MOH/JM/DS | PHOTOGRAPHS [illegible] N-15y [illegible] N-15 [illegible] N-15z [illegible] | TIME 1030

TIDE STAGE LOW LOW @ 0944 (+0.2) | WEATHER mostly clear | WIND SPEED 5-10 mph | WIND DIRECTION NNW

PROFILE ANGLE same as before | WAVE HT. 30 cm | SAMPLES TAKEN: BIO ____ CHEM T-A: 10 T-B: 138 | SED ____

SEDIMENT TYPE B/C/P



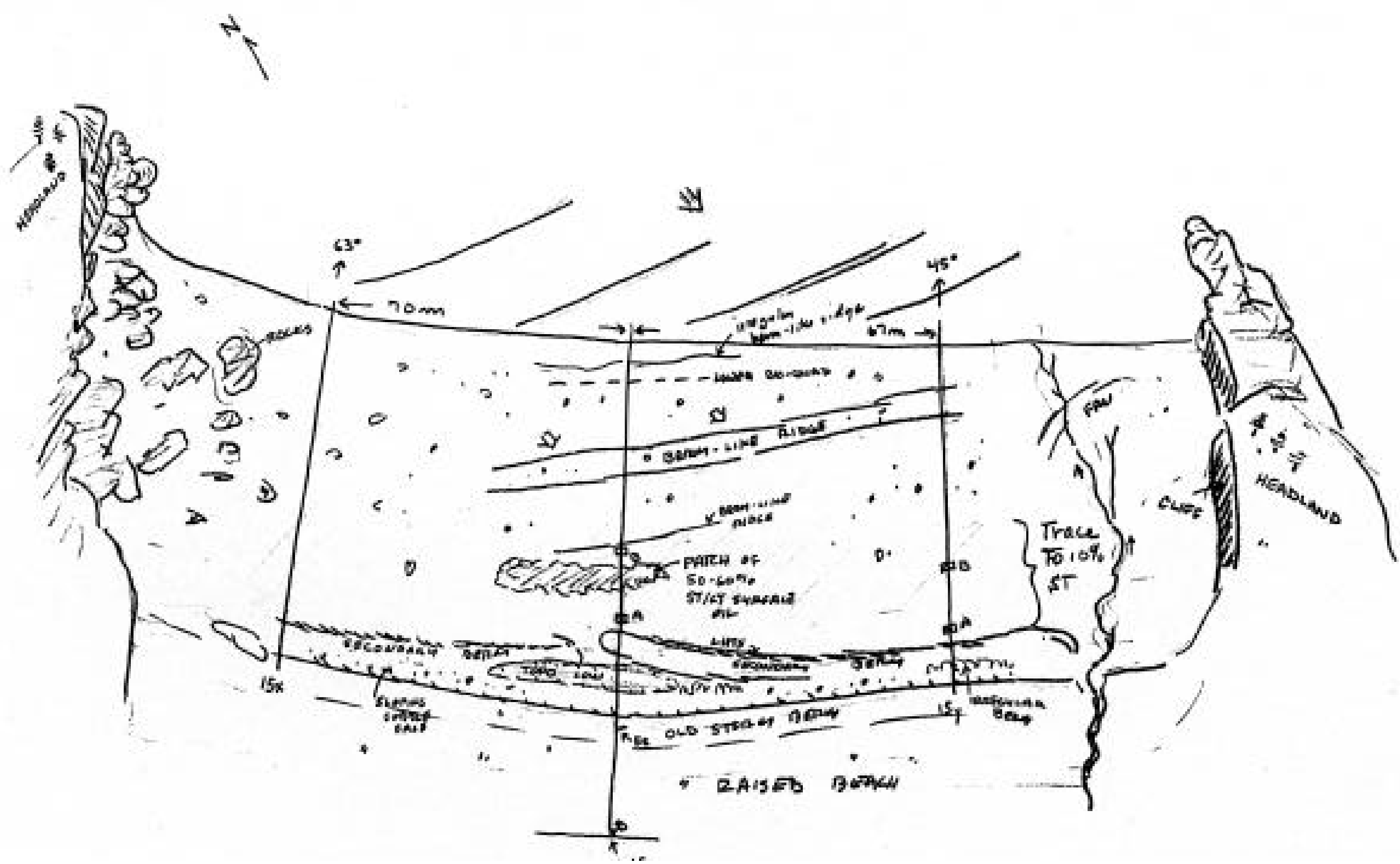
PROFILE LA-15 (N-15x, N-15, N-15y) LOCATION Latouche Island, PWS, AK DATE 28 AUGUST 1991

RECORDERS MOH/JW/DS PHOTOGRAPHS EVAL(47)-5(1-24), EVAL(47)-6(1-23) TIME 1030

TIDE STAGE Low @ 0944 (+0.2) WEATHER mostly clear WIND SPEED 5-10 mph WIND DIRECTION NNE

PROFILE ANGLE ____ WAVE HT. 30 cm SAMPLES TAKEN: BIO ____ CHEM TrA-1B, TrB (2B, 3B) SED ____

SEDIMENT TYPE B-C-P



Station No. ____________ Date________

1	DIST	ELEV	GRAIN SIZE(%)	SURFACE OIL	Flag	Activity	Oil	Bio	Sample	Sample	Comments
2			B/ C/ P/ G/ S	%/Type/Thick	No.		Interval	Zone	No.	Depth	
3											
4											
5											
6											
7											
8											
9											
10											
11											
12											
13											
14											
15											
16											
17											
18											
19											
20											
21											

(HS)
photos 15-23

Station No. N-15 Date 28 AUGUST 1991

Page 1

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DIST	ELEV	GRAIN SIZE(%)	SURFACE OIL	Flag	Activity	Oil	Bio	Sample	Sample	BS= 131 (top of scarp) ; FS= ... ; Observers MOH/JH/DS
		B/ C/ P/ G/ S	%/Type/Thick	No.		Interval	Zone	No.	Depth	Comments BS; NOAA sign
354	-56	grass								raised beach
199	-52	"								
301	-59	"								
369	-59	"								
525	-57	"								
368	-21	in logs								base of FS; on old storm berm (?)
142	-18	grass								base of scarp
167	-53	0/10/90/0/0	no oil							wood debris
422	-43	0/1/99/0/0	↓							edge of disturbed pebble berm; seatbelt / log debris
89	-16	0/60/40/0/0								LHTS
249	-31	0/60/40/0/0	↓							in hole; disturbed area (irregular landward) of C/B berm
228	+3	2/85/13/0/0								top of active HT berm
197	-4	2/98/0/0/0								crest of " " "
176	-32	2/95/3/0/0	2% ST	✓	TRENCH A	0-60cm (LOR)		1B	25-50cm	begin oiled clasts ↓ C/B platform
287	-23	5/90/5/0/0	50% ST (???)							
232	-15	20/80/0/0/0	60% ST & CT							
147	-20	20/79/1/0/0	50%, ST & CT	✓	TRENCH B	0-60cm (LOR-MOR)		2B 3B	35-45cm (LOR) 55-60cm (MOR)	
262	-8	25/75/0/0/0	30% " "							crest of berm-like ridge
273	-36	40/60/0/0/0	3% ST							

SHORELINE OIL TERMINOLOGY/CODES Version 2/9/91

SURFACE OIL DESCRIPTION

Discrete Oil Deposits

NO	No Visible Oil
TB	Tarball (<10 cm diameter)
PT	Patty (>10 cm diameter)
AP	Asphalt Pavement (oil-saturated gravel >1 meter diameter)
TM	Tar Mat (thick, soft oil accumulation at toe of beachface)

Continuous Oil Deposits

FL	Film or Sheen on Sediment Surface
ST	Stain (<0.1 mm thick; cannot be scratched off)
MO	Mousse (emulsified oil which has not penetrated into substrate)
CO	Coat (dried oil on rocks or cobbles which can be scratched off)
CR	Crust (dried oil on sediments which has not penetrated substrate)
PO	Pooled Oil (> 1cm thick on beachrock or bedrock surface)

SURFACE OIL DISTRIBUTION

/C	Continuous (90-100% coverage)
/B	Broken (50-90% coverage)
/P	Patchy (10-50% coverage)
/S	Sporadic or Splashes (<10% coverage)

SUBSURFACE OIL DESCRIPTION

Sand

SL	Surface Layer (oiled sediments extending from the surface)
BL	Buried Layer (a layer of oiled sediments overlain by clean sediments)
ML	Multiple Layers (multiple layers of clean and oiled sediments)

Gravel

OP	Oil fills Pore spaces between sediments
OR	Residual Oil coat on sediments or in pore spaces but not saturated
OF	Thin Film of residual Oil on sediments

DEGREE OF SHORELINE CONTAMINATION

H	Heavy (greater than 50% coverage of the intertidal zone with oil)
M	Moderate (between 25 and 50% coverage of the intertidal zone with oil)
L	Light (between 5 and 25% coverage of the intertidal zone with oil)
VL	Very Light (less than 5% coverage of the intertidal zone with oil)

SHORELINE ZONATION

Beaches		Tidal Flats	
BT	Berm Top	UF	Upper Flat
BF	Beachface	LF	Lower Flat
LT	Low-Tide Terrace	CL	Tidal Channel Levee

SUBSTRATE DEFINITIONS

BR	Beachrock/Bedrock	CS	Coarse Sand (0.5-2 mm)
B	Boulder (>256 mm)	MS	Medium Sand (0.25-0.5 mm)
C	Cobble (64-256 mm)	FS	Fine Sand (0.0625-0.25 mm)
P	Pebble (4-64 mm)	SI	Silt (<0.0625 mm)
Gr	Granule (2-4 mm)		

OILED DEBRIS TYPES

W	Woody Debris	/LG	Large Amounts
V	Vegetation	/MD	Moderate Amounts
T	Trash	/SM	Small Amounts

VEGETATION

HP	Halophytes	AL	Algal mats/beds
MG	Mangroves	SG	Seagrass Beds

SHORELINE SURVEY FORM 2/9/91

SITE NAME________________________ NO._______ DATE__/__/91 TIME______to______
OBSERVERS____
SITE LENGTH__________m LOW TIDE time______elevation_____
SHORELINE GEOMORPHOLOGY____
UPLAND DESCRIPTION____
SUBSTRATE: BR___% B___% C___% P___% Gr___% CS___% MS___% FS___% SI___%
WAVE EXPOSURE:_____Low_____Med_____High
CONTAMINATION LENGTH: H_____m M_____m L_____m VL_____m NO_____m

SURFACE OIL

DESCRIPTION	DISTRIBUTION				ZONE					
	C	B	P	S	BT	BF	LT	UF	LF	CL
Pooled Oil										
Crust										
Coat										
Mousse										
Stain										
Film										
Patties										
Tarballs										
No Oil										

No.	LENGTH (m)	WIDTH (m)	THICK (cm)
Asphalt Pavements			
Tar Mats			

OILED DEBRIS

	AMOUNT		
Woody	SM	MD	LG
Vegetation			
Trash			

SUBSURFACE OIL

TRENCH NO.	DEPTH (cm)	ZONE	SUBSURFACE OIL DESCRIPTION SL	BL	ML	OP	OR	OF	OIL INTERVAL (cm-cm)	WATER TABLE (cm)	SUBSTRATE TYPES

COMMENTS:

SKETCH MAP

Site Name________________

Site No.________

Date_________

Names________

Checklist

__North Arrow
__Scale
__Oil Distribution
__High Tide Line
__Low Tide Line
__Substrate Types
__Trench Locations

Legend

$^1\Delta$

Trench Number.
No Subsurface Oil

$^2\Delta$

Trench Number.
Subsurface Oil

SKETCH MAP

POINT HELEN, PWS, AK

Site Name KN-405A
Site No. near NOAA's site N-1
Date 4 JUNE 1991
Names T. Kelly (EXXON), M. Cramer, M. Hayes (NOAA), B. Trimm (")

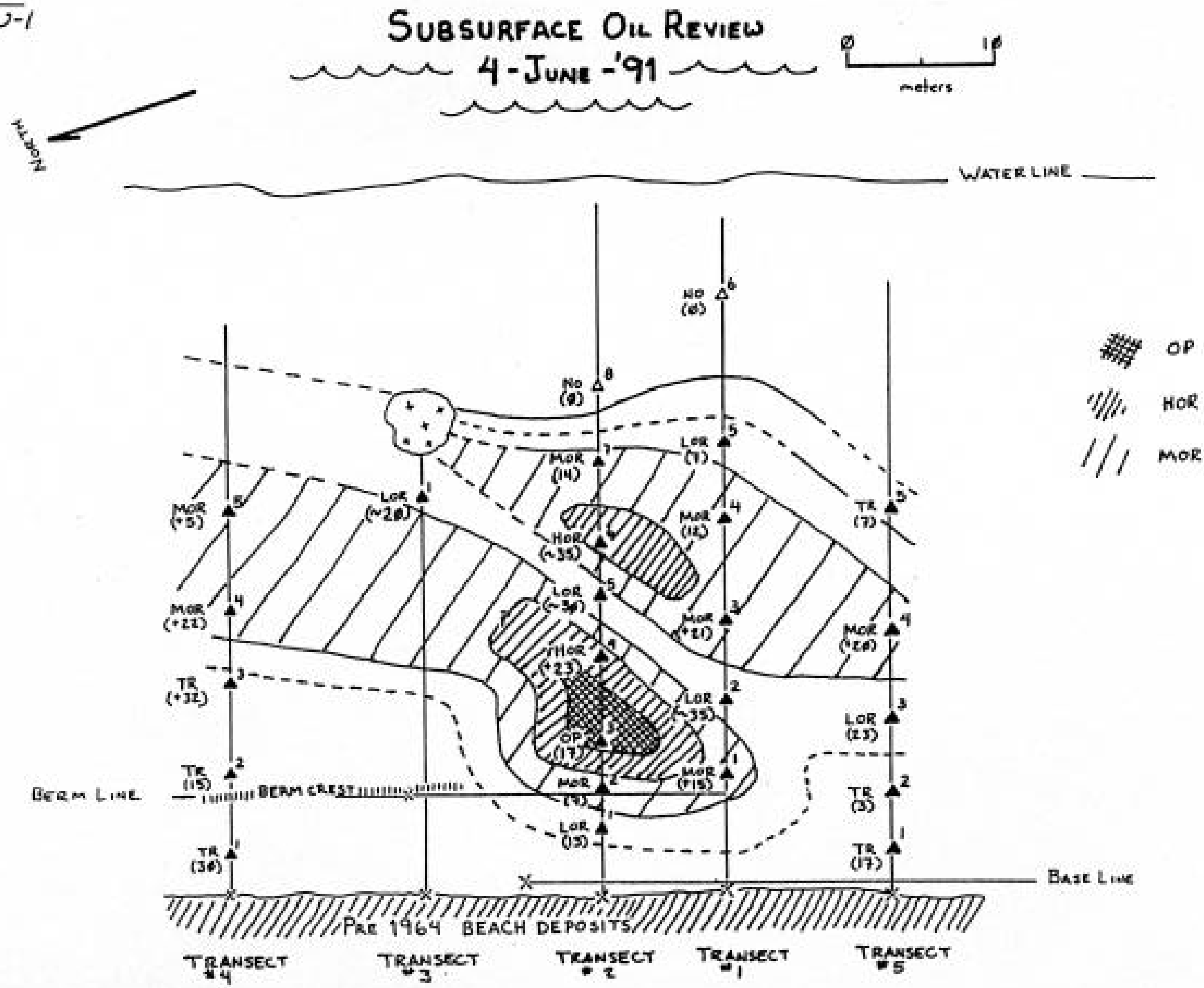
Checklist

✓ North Arrow
✓ Scale
✓ Oil Distribution
_ High Tide Line
_ Low Tide Line
_ Substrate Types
} on second map
✓ Trench Locations

Legend

1△
Trench Number.
No Subsurface Oil

2▲
Trench Number.
Subsurface Oil



Map by Bryan Trimm of Woodward Clyde, Inc. (for EXXON)

Trench Description Form

No. ___ Oil Sediments

Depth (cm) 0

Comments:

No. ___ Oil Sediments

Depth (cm) 0

Comments:

No. ___ Oil Sediments

Depth (cm) 0

Comments:

No. ___ Oil Sediments

Depth (cm) 0

Comments:

No. ___ Oil Sediments

Depth (cm) 0

Comments:

No. ___ Oil Sediments

Depth (cm) 0

Comments:

No. ___ Oil Sediments

Depth (cm) 0

Comments:

No. ___ Oil Sediments

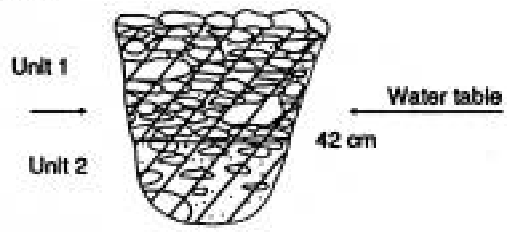
Depth (cm) 0

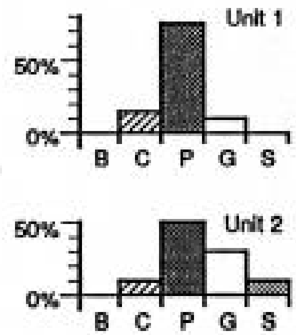
Comments:

KN405A POINT HELEN, 23 JANUARY 1991

- Oiled Zone

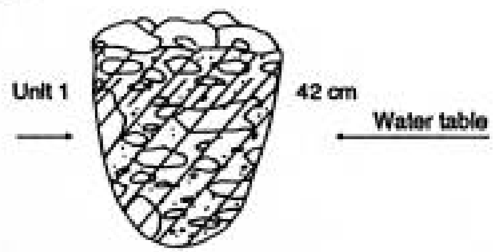
TRENCH A

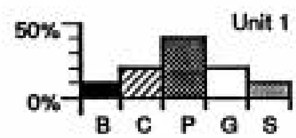




- Inversely graded
- Subangular to subrounded clasts
- Medium oil stain, heavy oil sheen on water table

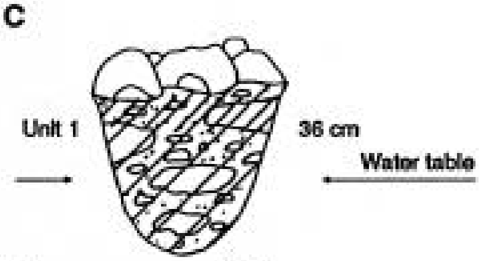
TRENCH B

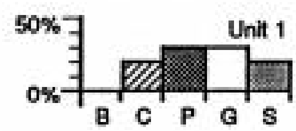




- Generally homogeneous material
- Crudely inversely graded
- Heavy oil stain throughout, with thick mousse layer floating on water table
- Boulder Armor
- Generally subrounded clasts

TRENCH C





- Generally homogeneous material
- Crudely inversely graded
- Medium oil stain throughout, heavy film on water surface
- Boulder Armor
- General subrounded clasts

Description of sediments in trenches dug at NOAA's station KN-405A on 23 January 1991. Note abundance of sand and granule material in subsurface sediments. See Figure 5 for location of trenches A and B. Trench C is located north of the profile a bit seaward of trench A.

7 Monitoring/Sampling

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Chapter 7. Monitoring/Sampling

Collecting and analyzing data

Introduction

There are numerous ways that sampling and monitoring enter into oil spill response activities. Frequently, some sampling will be done immediately after the spill to help determine the immediate response. Taking samples of the oil to determine a "fingerprint" (identify the source of the oil) is one example. Some response activities will be approved contingent on a monitoring program being conducted, such as using dispersants, or bioremediation. In these cases, oil spill response personnel will find themselves involved in decisions regarding monitoring programs that are conducted in conjunction with these response techniques.

Response personnel may also, on occasion, wish to initiate monitoring projects themselves. These could be simple projects designed to answer questions about the effectiveness of a particular response, or to provide follow up monitoring after a spill. Knowing what environmental impacts were associated with the spill as well as the response activities can be very useful information that may be applicable when responding to future spill events.

Though not all spill response personnel will be directly involved in the collection of samples and the design of experiments, they will be in positions where they need to interpret data and make decisions based on these interpretations. Some possible examples include determining the validity of studies of new response techniques, evaluating bioassays to determine if adverse environmental effects can be expected, or evaluating studies on the effectiveness of particular treatments.

Even a basic knowledge of statistics and a minimum comfort level with analyzing data will help to defuse the "mystique" often inspired by the use of data and numbers. Being able to form one's own opinions about studies and results will provide a real advantage over having to rely on someone else's interpretations, especially in a field that is as politically charged as oil spill response.

Establishing objectives and endpoints

Objectives

Stating a clear objective often seems so obvious that it is not explicitly mentioned by people considering sampling projects. However, it is frequently the case that objectives are not well thought out, and consequently, data is collected that does not answer the question originally intended. When objectives are clearly defined and explicitly stated, then hypotheses and sample designs follow easily from them. Figures 7-1 and 7-2 present several examples of objectives that might be used in studies associated with oil spill response.

Hypotheses

Though not all sampling plans and experiments will involve the use of formal hypotheses, many questions lend themselves to a simple hypothesis test, which can then be subjected to a statistical test. An hypothesis is merely a restatement of the objective in statistical language that can later be subjected to a statistical test, where the hypothesis will be accepted or rejected, depending on the data results. Experiments that have several components may have several different hypotheses. Formulating an explicit hypothesis will also necessitate selecting the endpoint to be used for determining whether the hypothesis is accepted or rejected.

Endpoints

Endpoints are specific measures of the objectives of the experiment, and determine how parameters such as “effectiveness” or “toxicity” or “similarity” will be measured. Endpoints should ideally be a measurable quantity, such as “the concentration of PAH in tissue, measured as dry weight,” or “the relative abundance of selected species counted in intertidal quadrats.” Endpoints may include qualitative data, as in the fingerprinting example in Figures 7-1 and 7-2, but the type of data and the way it will be used should be specified as closely as possible. To establish endpoints, any

Bioremediaton

Effectiveness: Will proposed bioremediation with 'BIO-Wonder' work here?

Objective:
Will the bioremediation treatment degrade oil faster or in greater quantities than background rates?

Hypothesis:
The mean TPH from plot A (oiled, treated) will be the same as the mean from plot B (oiled, untreated)

Null hypothesis:
Ho: X_a (treated) = X_b (untreated)

Endpoint:
Chemical measurement of total petroleum hydrocarbon (TPH) in sediment samples collected from each plot.

Toxicity: Will 'Bio-Wonder' harm the environment?

Objective:
Will 'Bio-Wonder' cause toxic effects to marine organisms?

Hypothesis:
Bioassays using oyster larvae will show the same acute mortality rates with 'Bio-Wonder' as with plain seawater

Null hypothesis
Ho: M_p (product) = M_s (seawater)

Endpoint:
Mortality of bivalve larvae after 48 hours

Figure 7-1. Examples of objectives, hypotheses and endpoints for a bioremediation example

Oil Fingerprinting
Is all the oil found on the beach from the spill?

Objective
Is the oil sampled from the beach the same as that carried by the stricken tanker?

Hypothesis
Oil collected from site A (on beach) is the same as oil collected from the slick emanating from the tanker

Null hypothesis
(Not applicable)

Endpoint
Gas chromatographs, will be compared between the two samples with a focus on specific tracer compounds.

Figure 7-2. Examples of objectives, hypotheses and endpoints for an oil fingerprinting example.

laboratories that will be used for analysis should be consulted prior to sampling to ensure that samples are handled appropriately. Though most people understand the need for objectives and even hypotheses, in many cases, even elaborate and costly experiments do not select *in advance* the endpoint that will be used to answer to the original question. This is especially pertinent for environmental parameters that may be difficult to define, as well as measure (for example, “biodegradation” or “environmental recovery”).

Two major problems can result from the failure to select an endpoint for an experiment:

1). The data collected may not have been handled appropriately for the analyses that are needed;
2). The type of data or the way it was collected may not be appropriate to answer the original objective.

Specific selection of endpoints is also very important when several parties are involved in an experiment, as is frequently the case with oil spill monitoring. At the conclusion of the project, it may be found that the data collected do not answer the question posed. Or, when several different kinds of data are collected, disagreement may ensue between the different parties involved over what constitutes the "real" endpoint, and thus, the "real" result.

Sampling design

An appropriate sampling design helps ensure that the data collected provide answers to the initial questions posed. Sampling designs may be simple or very complex, but they should follow after the objectives and endpoints that have been selected. Sample design includes consideration of control sites, the number of samples, the locations where samples will be collected, the timing of sampling, and sample handling and analysis. For monitoring or sampling projects other than very simple ones, the best procedure will be to consult with a statistician while still in the planning stage.

Controls

A crucial part of most experiments is the reference or control site. Most objectives will involve detecting differences, or making comparisons, and thus require a baseline, or reference from which to measure change. In the absence of some sort of reference, interpreting the data will be difficult and possibly meaningless. In theory, controls should be replicates of the tested plot or experimental unit, the same in every way, except for the treatment applied. Some examples of possible controls are listed below:

- For a laboratory flask test: seawater containing no product (e.g. dispersant or bioremediation) at the same salinity and temperature as in the treated flask

- For a field study: a marsh plot containing the same plant species, with similar densities and oiling effects as the treated plots

In practice, control sites in field studies will never be completely identical to the test sites. Usually, one must settle for a "representative control" that is as similar or as representative as is feasible. Other options include the use of experimental units placed in the environment, such as sediment boxes. This technique was used by Berge (1990) to study colonization of biota to sediments impacted by oil, compared with control sediments.

One way to establish controls at spills of opportunity is by the use of "set-asides" (areas that are impacted by oil that are set aside, and left untreated for experimental purposes). NOAA arranged for such "set asides" immediately after the *Exxon Valdez* spill. Having these sites made it possible to conduct the long term study of treatment effects in Prince William Sound that is still ongoing.

Numbers of samples

The number of samples to be collected will depend on:

- the question being asked,

- the kind of data analysis to be done (including the statistical certainty desired)

- practical considerations (area available, time and access, personnel, cost)

A larger number of samples often allows greater power for statistical analysis, but will be more costly. If the parameter being measured is highly variable, such as the distribution of oil in sediments, a large number of samples will be needed to have the power necessary to conduct statistical testing. A small number of samples will provide an indication of the processes occurring, but may not be representative of the entire study area. One strategy is to collect a large number of samples in the field and then to analyze only a subset of the samples collected, based on the initial results.

In many field sampling situations, the number of samples that can be collected will be limited by logistics and practical considerations. These may include the area available, time and access constraints, personnel, cost, etc. In any event, it will almost always be more useful to take a few carefully thought-out samples than to take numerous samples without proper planning and subsequent follow-through.

Locations of samples

The locations chosen for sampling will depend on the number and types of habitats or shoreline types to be investigated, as well as on the sample analysis that will be conducted. A common approach is to select one or more plots to be sampled, with each plot representing a particular environment or treatment. Then, random sampling can be conducted within each plot. In a marsh monitoring, for example, transects could be placed in a control marsh, a trampled section of marsh, and in a washed section of marsh. Then replicate quadrats would be located randomly along each quadrat.

When possible, it is best to avoid taking samples in areas with outside influences that may confound the results, such as areas near outfalls or freshwater streams. Samples taken in the middle of a plot will usually be more representative than samples taken along the edge. One method for locating samples within a plot is to lay a grid pattern over a map of the test area and choose samples randomly in each designated area. (See Figure 7-3 for examples of different sample designs using plots).

Timing of sample collection

Timing refers to both the duration of the experiment, and the frequency with which samples will be collected. This could vary from a one-time sample collection, up to a multi-year monitoring program where sampling is conducted seasonally. As for other aspects of sample design, the appropriate time frame for collecting samples will depend on the questions being addressed. For this, one must refer back to the original objectives.

Some preliminary information will be helpful when determining both duration and frequency. For instance,

- Does the parameter of interest vary seasonally?
- Is there a minimum length of time necessary for acquiring useful information from the sampling program?

Dispersant monitoring, for example, will be conducted on a very short time frame, on the order of a several hours to days. Bioremediation, in contrast, must be sampled over a period of at least a week, and preferably over several weeks to be able to detect biodegradation. Ecological processes are ideally monitored seasonally over a long time frame, of several years duration, if possible.

Qualitative and quantitative data

Data can be categorized into two rough types, qualitative and quantitative.

Qualitative data is best described as descriptive; information that helps describe something, and gives the experimenter general background information. Qualitative data does not enable one to attribute a degree of certainty to the conclusions, since it does not include measures of variance. Because of this, qualitative data cannot be extrapolated to a larger environment or population.

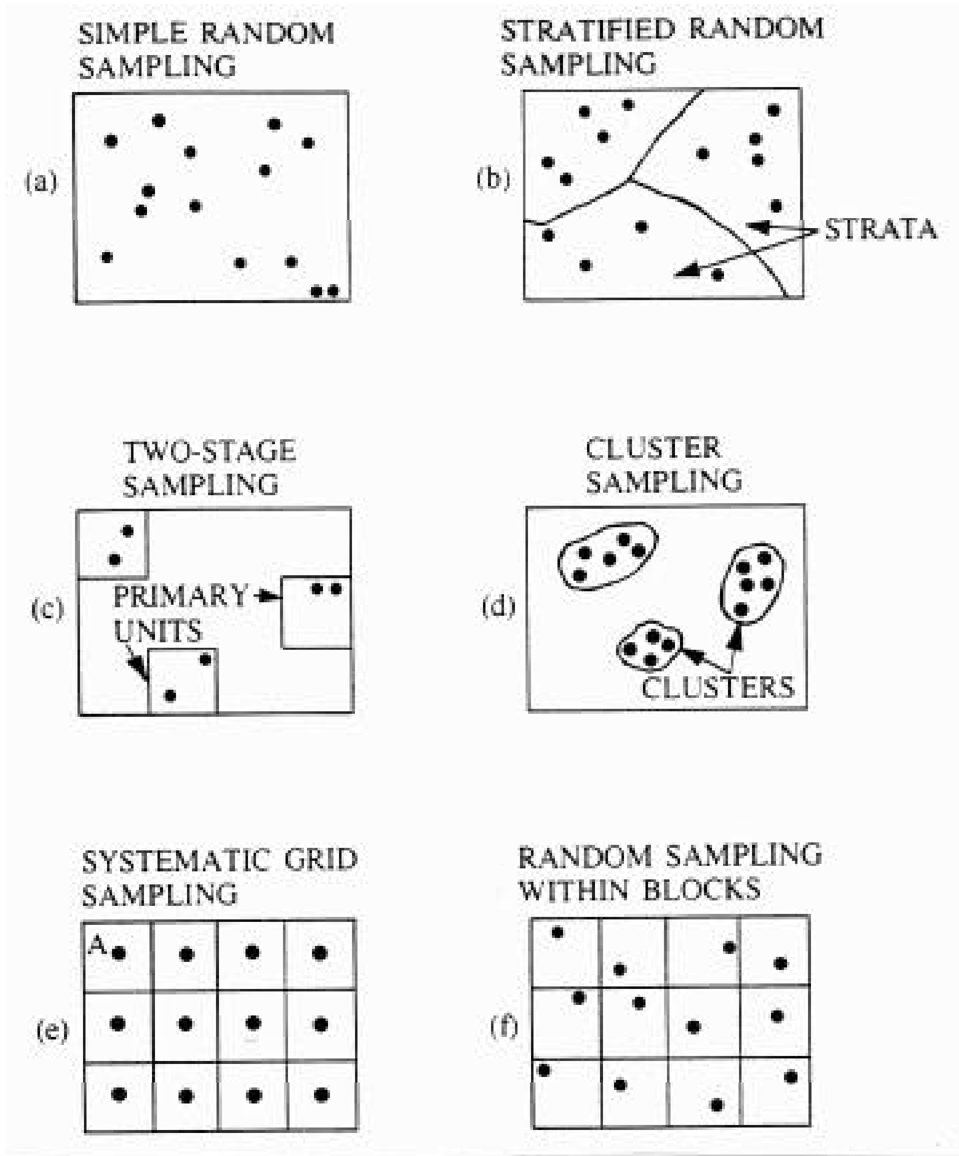

Figure 7-3. Some two-dimensional probability sampling designs for sampling over space (NAS 1985).

Qualitative data is useful for data exploration purposes, for identifying possible trends, and for "getting a feel for what is going on." Certain kinds of investigations are, by nature, descriptive, such as those that would address the following questions:

What kind of oil is this?
What type of habitat is this?

What species of plants or animals live here?

Initial, or pilot investigations will often be qualitative, and serve as a first source of information to use in developing future sampling plans. Field observations, made in the form of simple field notes, are very important types of qualitative data. Observations from people on the scene, that record things such as weather patterns, unusual occurrences, where oil was observed, etc. may be very helpful in clarifying what actually happened at a later date.

Qualitative data is limited, in that it cannot be used in the following ways:

- Extrapolating to broader universes
  (the sample collected may not be representative of other areas)

- Statistical testing
  (all statistical tests assume certain things about the data, for instance, that the samples were collected in a randomized manner)

Quantitative data means data that has been collected from random sampling, with some measure of variability (replication), and is representative of a larger population or universe. Quantitative data will usually result from a carefully planned experimental design. The advantages of this type of data area that there are many options for analysis, including performing statistical tests, and attributing statistical significance to the results.

As discussed earlier, it is by no means always necessary to obtain quantitative data. If the objective can be met by a simple collection of qualitative data, then there may be no reason to conduct more elaborate sampling.

Some considerations for analyzing data

When looking at your own or data collected from other sources, it is important to be on the lookout for measures of uncertainty that might make the results questionable. Two sources of uncertainty in sampling are bias and systematic sampling errors. Bias could result if something in the sampling plan or the sample collection makes the samples not representative of the population being studied. Systematic errors stem from errors that occur while sampling such as malfunctioning equipment.

When laboratory analyses are performed, look for the existence of a quality assurance, quality control program that cross-checks laboratory work. Also examine the detection limits of the work, to know the degree of accuracy of the data.

Some simple ways to gather data

Useful information can be gathered by people who will be on scene at incidents in several ways that do not involve excessive cost or effort. Some examples of these are as follows:

- Establish intertidal transects on shorelines
  - survey species found along the transects
  - survey the species found inside quadrats
  - photograph the transect and/or the quadrats to determine percent cover of vegetation or invertebrates

- Establish test plots corresponding to different treatment techniques

- Observe impacted areas over time
  - re-visit the site at definite intervals (seasonal, monthly)
  - take photographs from marked areas or known vantage points

Summary

- Objectives, hypotheses and endpoints should be clearly specified before a sampling project is designed

- Sample design will include the following:
  - Proper controls,
  - An appropriate number of samples (this will depend on the analysis to be conducted),
  - Locations representing the habitats being studied,
  - Duration and frequency of sampling appropriate to the objectives.

- Qualitative data is descriptive in nature and cannot be extrapolated to broader populations

- Quantitative data can be used for statistical testing, but must be from random samples

- Uncertainty in data can result from
  - biases in sampling, or systematic errors
  - errors in analysis (check for quality control and detection limits)

- Some simple ways to monitor
  - establish transects
  - use photography
  - establish plots by treatment
  - re-visit impacted sites

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8 The Archetypical Environmental Sensitivity Index

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Chapter 8.
The Archetypical Environmental Sensitivity Index

Introduction

Environmental Sensitivity Index (ESI) maps have been an integral component of oil spill contingency planning and response since 1979, when the first ESI maps were prepared days in advance of the arrival of the oil slicks from the *Ixtoc 1* well blowout in the Gulf of Mexico. Since that time, ESI atlases have been prepared for most of the U.S. shoreline, including Alaska and the Great Lakes. Figure 8-1 shows the areal coverage of existing ESI atlases and Table 8-1 lists the publication date, number of maps, and scale for each atlas. With the exception of northern and central California, central Texas, and Mississippi, all of the atlases have been prepared with funding by the National Oceanic and Atmospheric Administration (NOAA). Furthermore, all the ESI atlases, except for those listed above and the Chukchi Sea in Alaska, were prepared using standardized methods and products (Hayes et al., 1980; Getter et al., 1981). Sensitivity mapping projects have also been conducted for coastal areas of France, Germany, Italy, Nigeria, Kuwait, Saudi Arabia, Oman, United Arab Emirates, Malaysia, and New Zealand, among others.

Traditional sensitivity maps have been produced in color-coded paper maps, of limited distribution (because of the cost of reproduction), and without a means for ready updating. With the advent of Geographic Information System (GIS) software for microcomputers, automation of ESI information has been a major new focus. Digital, georeferenced databases are being developed for natural resources management at federal, state, and local levels. These digital databases can provide a ready source for development of automated sensitivity maps for oil spills. With the power of GIS, sensitivity mapping moves from a static product of limited distribution to a valuable tool for planning and response to oil spills. The first use of GIS technology for production of ESI maps was in Louisiana, where satellite imagery was used to update air photograph interpretations to produce the base maps and intertidal habitat rankings. The technique is being further refined for NOAA by RPI into an all-digital ESI product for southeastern Alaska.

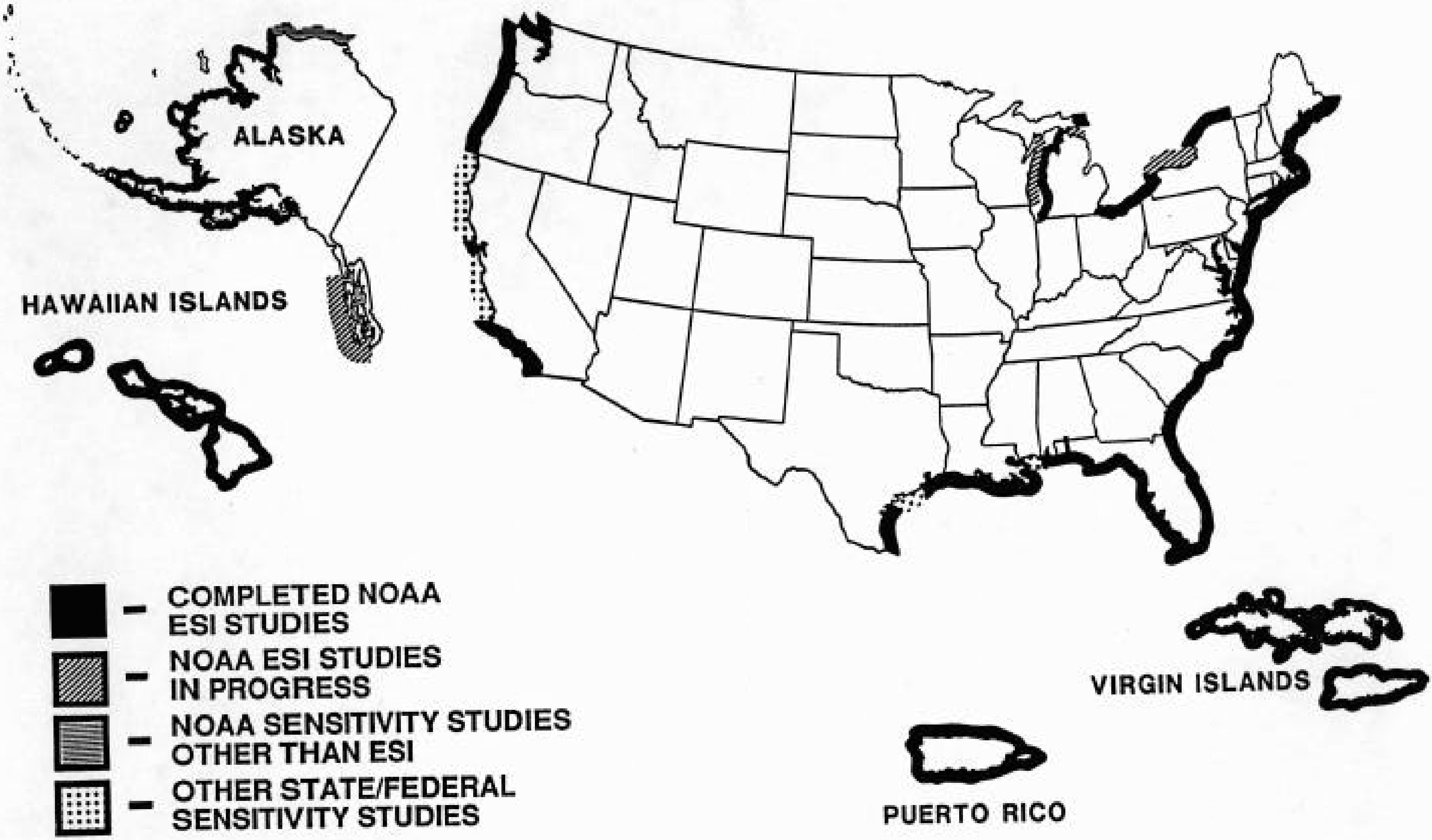

Figure 8-1. Status of Environmental Sensitivity Index mapping.

Table 8-1. Listing of all environmental sensitivity index (ESI) atlases published for the United States.

Name	Year Published	No. of Maps	Map Scale
Alabama	1981	20	1:24,000; 1:62,500
Alaska	1982-1986	371	1:63,360
California	1980-1986	75	1:24,000; 1:40,000
Connecticut	1984	17	1:24,000
Delaware/New Jersey/ Pennsylvania	1985	59	1:24,000
Florida	1981-1984	217	1:24,000
Georgia	1985	29	1:24,000
Hawaii	1986	86	1:20,000; 1:24,000 1:32,500; 1:40,000 1:62,500; 1:80,000 1:100,000
Louisiana	1989	98	1:50,000; 1:95,000 1:100,000; 1:105,000
Maine	1985	77	1:24,000; 1:40,000
Maine/New Hampshire	1983	25	1:24,000; 1:40,000
Maryland	1983	119	1:24,000
Massachusetts	1980	49	1:24,000
Michigan	1985-1986	38	1:24,000; 1:50,000 1:62,500; 1:163,360
New York	1985	77	1:24,000; 1:50,000
North Carolina	1983	113	1:24,000; 1:62,500
Lake Erie	1985	66	1:24,000; 1:62,500
Oregon/Washington	1986-1989	81	1:24,000; 1:62,500
Puerto Rico	1984	35	1:20,000
Rhode Island/Massachusetts	1983	18	1:24,000; 1:25,000
South Carolina	1982	50	1:24,000
Texas	1979-1980	34	1:24,000; 1:40,000
U.S. Virgin Islands	1986	8	1:24,000
Virginia	1983	113	1:24,000
Washington	1984-1985	80	1:24,000; 1:62,500
Total		1,954	

As the oil spill response community moves towards development of automated sensitivity maps, it is important to define what comprises the archetypical ESI mapping system. This guideline can help define the collection of data for the system, allowing for regional differences in resource distribution, data availability and currency, and extent of supporting information. The primary objective of this analysis is to outline the basic elements of a sensitivity mapping system. The second objective is to describe how sensitivity maps are used for contingency planning and during spills. These uses will drive the development of automated systems, the user interface, pre-set queries, standardized output formats, and map symbology.

Elements of an Environmental Sensitivity Mapping System

General Coverage and Types of Information

The areal coverage of existing marine sensitivity maps is along the coastal zone and extending up rivers to the "head of tide," or the furthest inland extent of tidal influence. Along coastal, navigable rivers, the ESI maps extend to the boundary of the U.S. Coast Guard response zone, except along the Mississippi River, where the ESI maps extend to Baton Rouge. Existing maps extend to Troy on the Hudson River, to Trenton on the Delaware River, and to the John Day Dam (river mile 215) on the Columbia River. As part of a special Florida project, the Appalachicola River was mapped to the upper reaches of Lake Seminole.

In the Great Lakes, all of Lake Erie, eastern Lake Michigan, St. Mary's River, and both sides of the St. Lawrence River from Lake Ontario to the New York/Canada border have been mapped. Work is currently underway to produce ESI atlases in digital format for the U.S. shoreline of Lake Ontario and the Wisconsin shoreline of Lake Michigan.

Nearly all of the maps of the lower 48 states have been prepared at a scale of 1:24,000, using U.S. Geological Survey (USGS) 7.5 minute quadrangles as the base map. There are a few exceptions where USGS maps were not available or at the appropriate scale. For all of Alaska, 15-minute USGS topographic quadrangles at a scale of 1:63,360 have been used as base maps. Southeast Alaska-Part I is being done as a totally digital product. Columbia River and Louisiana have been produced with the intertidal shoreline types in digital format.

ESI maps are comprised of three general types of information:

1) Habitats–which are further divided into:

   A) Intertidal shoreline habitats, which are ranked according to a scale relating to sensitivity, natural persistence of oil, and ease of cleanup.

   B) Subtidal habitats, which are utilized by oil-sensitive species or are themselves sensitive to oil spills, including eelgrass beds, kelp, and coral reefs.

2) Biological Resources–including oil-sensitive animals and plants.

3) Human-Use Resources–specific areas that have added sensitivity and value because of their use by humans, such as high-use amenity beaches, parks and marine sanctuaries, water intakes, and archaeological sites.

Each of these elements are briefly discussed in the following section.

Habitats

Intertidal Shoreline Types.–Intertidal habitats are at risk during spills because of the high likelihood of being directly oiled when floating slicks impact the shoreline. Oil fate and effects vary significantly by shoreline type, and many cleanup methods are shoreline-specific. The concept of mapping coastal environments and ranking them on a scale of relative sensitivity was originally developed in 1976 for lower Cook Inlet (Michel et al., 1978). Since that time, the ranking system has been refined and expanded to cover shoreline types for all of North America, including the Great Lakes and riverine environments. Table 8-2 lists the various existing ESI classifications for intertidal shoreline types. There are significant regional differences, to account for the different coastal types. For most areas, the 1-10 scale was used, with subdivision of the numerical ranking for different shoreline types with similar relative sensitivity.

Table 8-2. Summary of the various ESI ranking scales used throughout the United States.

ESI NO.	ALASKA	WEST COAST	COLUMBIA RIVER	TEXAS
1	Exposed rocky shores	Exposed rocky shores/seawalls	Unvegetated steep banks and cliffs	Exposed scarps
2	Wave-cut platforms	Wave-cut platforms	Sand/gravel beaches	
3	Fine sand beaches	Fine sand beaches	Riprap	Exposed fine-grained sand beaches
4	Coarse sand beaches	Coarse sand beaches	Flats	Sheltered fine-grained sand beaches
5A	Exposed tidal flats (low biomass)	Sand and gravel beaches	Vegetated banks	Exposed tidal flats (low biomass)
5B				
6A	Sand and gravel beaches	Gravel beaches /exposed riprap	Marsh/swamp	Mixed sand and shell beach
6B				
7A	Gravel beaches	Exposed tidal flats		Exposed tidal flats (moderate biomass)
7B	Exposed tidal flats (high biomass)			
8A	Sheltered rocky shores	Sheltered rocky shores and coastal structures		
8B				
9	Sheltered tidal flats	Sheltered tidal flats		Sheltered tidal flats
10A	Marshes	Marshes		Salt marshes
10B				
11				

Table 8-2. Continued.

ESI NO.	LOUISIANA	FLORIDA/PUERTO RICO/USVI	SOUTHEAST (AL/GA/SC)	MID-ATLANTIC (MD,VA,NC)
1	Developed/ unforested upland	Exposed rocky shores/seawalls	Exposed seawalls	Consolidated shores/seawalls
2	Sand beach/spoil bank	Exposed rocky platforms	Not present	Exposed fine sand beaches
3	Tidal mudflat	Fine sand beaches	Fine sand beaches	Sheltered fine sand beaches
4	Freshwater flat	Coarse sand beaches	Coarse sand beaches	Coarse sand beaches
5A	Salt marsh	Sand/gravel beaches	Sand and shell beaches	Exposed tidal flats
5B	Fresh marsh			
6A	Swamp	Gravel beaches/ Riprap	Riprap	Riprap
6B				
7A	Mangroves	Exposed tidal flats	Exposed tidal flats	Supratidal marshes
7B				
8A		Sheltered rocky shores/seawalls	Sheltered seawalls	Freshwater marsh/swamps
8B				
9		Sheltered tidal flats	Sheltered tidal flats	Sheltered tidal flats
10A		Exposed marshes/ mangroves	Marshes	Fringing intertidal marshes
10B		Sheltered marshes/ mangroves	Sheltered marshes	
11				Extensive intertidal marshes

Table 8-2. Continued.

ESI NO.	DEL/NJ/PA	NORTHEAST (NY to ME)	GREAT LAKES	APALACHICOLA RIVER
1	(Not present)	Exposed rocky shores	Exposed bedrock bluffs/seawalls	Vertical rocky shores/seawalls
2	Eroding bluffs	Wave-cut platforms	Exposed unconsolidated sediment bluffs	Exposed bluffs
3	Fine sand beaches	Fine sand beaches	Shelving bedrock shores	Fine sand beaches
4	Coarse sand beaches	Coarse sand beaches	Sand beaches	Coarse sand beaches
5A	Sand and gravel beaches	Sand and gravel beaches Exposed tidal flats (MA)	Sand and gravel beaches	Mixed sediment beaches
5B				
6A	Gravel beaches	Gravel beaches	Gravel beaches	Gravel beaches, riprap, and cross levees
6B	Riprap	Riprap		
7A	Exposed tidal flats	Exposed tidal flats	Riprap structures	Exposed tidal flats
7B				Vegetated bluffs
8A	Vegetated riverine banks	Sheltered rocky shores	Sheltered bluffs (bedrock)	Vegetated low banks
8B			Sheltered impermeable structures	
9	Sheltered tidal flats	Sheltered tidal flats	Low banks	Cypress/hard-wood swamps
10A	Marshes	Marshes	Fringing wetlands	Freshwater marshes
10B			Extensive wetlands	Saltwater marshes
11				

The intertidal ranking scheme is based on an understanding of the coastal environment, not just the substrate type and grain size. The sensitivity ranking is an integration of the:

1) Shoreline type (substrate, grain size, tidal elevation, origin),
2) Exposure to wave and tidal energy,
3) Analysis of the natural persistence of the oil on the shoreline,
4) Biological productivity and sensitivity, and
5) Ease of cleanup without causing more harm.

All of these factors are used to determine the relative ESI ranking for a shoreline segment. Key to the rankings is an understanding of the relationships between physical processes and substrate which produce specific geomorphic shoreline types and predictable patterns in oil behavior and sediment transport patterns. Historically, the rankings were defined from field surveys and literature analysis, then mapped directly as the shoreline type during aerial surveys. The most common shoreline rankings used in the U.S., with a short summary of the oil behavior, biological sensitivity, and ease of cleanup, are listed below.

1) <u>Exposed, vertical rocky shores and seawalls.</u>

   These shoreline types are exposed to high wave energy or tidal currents, which tend to keep oil offshore by reflecting waves. The substrate is impermeable so oil remains on the surface where natural processes will quickly remove any oil that does strand. Also, any stranded oil tends to form a band along the high-tide line or splash zone, above the elevation of the greatest biological value. No cleanup is required or recommended. Along developed shorelines, exposed concrete seawalls and steel bulkhead are man-made equivalents.

2) <u>Wave-cut rocky platforms, scarps in clay, and exposed sedimentary bluffs.</u>

   These shorelines are also low in rank because they are exposed to high wave energy. However, they have a flatter intertidal zone, sometimes with small accumulations of sediment at the high-tide line, where oil could persist for up to several weeks to months. Biological impacts can be severe, particularly if there are tidal pool communities on the rocky platforms. Cleanup is not necessary except for removal of oiled debris and tarballs at the high-tide line in areas of high recreational use or to protect a nearshore resource.

3) Fine-grained sand beaches.

Compact, fine-grained sand beaches inhibit oil penetration, and, as they generally accrete very slowly between storms, the depth of oil burial is minimal. Cleanup is simplified by the hard substrate. Biological utilization is low and populations can recover after a few months.

4) Coarse-grained sand beaches.

Coarse-grained sand beaches are ranked higher because of the potential for higher oil penetration and burial, which can be as great as one meter. Cleanup is more difficult, as equipment tends to grind oil into the beach because of the loose packing of the sediment.

5) Mixed sand and gravel beaches.

Because of higher permeabilities, oil tends to penetrate deeply into sand and gravel beaches, making cleanup by removal of contaminated sediment difficult without causing erosion and sediment disposal problems. These beaches undergo seasonal variations in wave energy and sediment reworking, so natural removal of deeply penetrated oil may only occur during storms with a frequency as low as 1-2 per year. Biological utilization is low, because of the sediment mobility and rapid drying during low tide.

6) Gravel beaches and riprap.

Gravel beaches are ranked the highest of all beaches primarily because of the potential for very deep oil penetration and slow natural removal rates of subsurface oil. The slow replenishment rate of gravel makes removal of oiled sediment highly undesirable, and so cleanup of heavily oiled gravel beaches is particularly difficult. For many gravel beaches, significant wave action (meaning large enough waves to rework the sediments to the depth of oil penetration) occurs only every few years, leading to long-term persistence of subsurface oil. Riprap is a man-made equivalent, with added problems because it is usually placed at the high-tide line where the highest oil concentrations are found and the clasts are not reworked by storm waves. Often, the only way to clean riprap is by removal and replacement.

7) Exposed tidal flats.

Oil does not readily adhere to or penetrate the compact, water-saturated sediments of exposed sand flats. Instead, the oil is pushed across the surface and accumulates at the high-tide line. Because of the high biological utilization, however, impacts to benthic invertebrates by exposure to the water-accomodated fraction or by smothering can be significant. Sometimes, highly mobile sand flats, such as those at the mouths of large inlets, are ranked lower when infaunal densities are low.

8) <u>Sheltered rocky shores and seawalls.</u>

Spilled oil tends to coat rough rock surfaces in sheltered settings, and oil persistence is long-term because of the low wave energy. Mapping should differentiate between solid rock surfaces which are impermeable to oil and rocky rubble slopes which tend to trap oil beneath a veneer of coarse boulders. Both types can have large amounts of attached organisms, supporting a rich and diverse community. Cleanup of these shorelines is always labor intensive and can affect biological communities.

9) <u>Sheltered tidal flats.</u>

The high biological utilization, soft substrate and low energy setting makes these habitats highly sensitive to oil spill impacts and almost impossible to clean. Usually any cleanup efforts result in mixing oil deeper into the sediments and prolonging recovery.

10) <u>Vegetated wetlands.</u>

Marshes, mangroves, and other vegetated wetlands are the most sensitive habitats because of their high biological utilization and value, difficulty of cleanup, and potential for long-term impacts to many organisms. Where there are multiple wetland types present, different rankings can be assigned based on likelihood of being oiled, relative wave energy, species composition, and geomorphology (see Virginia rankings in Table 8-2).

With GIS capabilities, it may be possible to build the shoreline sensitivity classification from other basic parameters, such as substrate, sediment size or type, elevation, width, slope, general geomorphology, general biological sensitivity, etc., then use algorithms to calculate exposure to wave and tidal energy for each shoreline segment and assign a sensitivity rank. However, this type of sensitivity ranking must be done in a highly supervised classification mode. Although existing intertidal habitat maps are a good source for mapping discrete classes, i.e., gravel, sand, or mud, they are not good sources when these classes are mixed (sand and gravel), and they do not contain the information needed to identify coastal geomorphological types. The existing ESI maps are usually the best source of information on intertidal habitats for ranking of shoreline sensitivity. The scale of mapping is usually at $\pm$100 feet for maps made on U.S. Geological Survey 7.5 minute quadrangles.

Development of a standardized sensitivity mapping protocol brings up some special questions on shoreline mapping issues.

- Should all intertidal habitats be ranked on a scale of 1 to 10?

- If so, should subdivisions into 5A, 5B, etc. be used for different shoreline types of similar sensitivity?
- Should an "ESI number" always refer to a specific shoreline type? That is, should ESI = 9 always be sheltered tidal flats?

From one perspective, the 1 to 10 ranking scheme is not as important as the shoreline classifications. The relative rank can be assigned or calculated based on the various factors listed above and attribute data. However, the ESI rankings have significant precedent and acceptance. If a 1 to 10 ranking was always used, then one would always know that the most sensitive shoreline type was ESI = 10, without having to consider that there might be an ESI = 11 type. Thus, the ESI numbers would not always refer to a specific shoreline type, but the relative sensitivity to the impacts of spilled oil. In fact, seldom has a responder asked about a shoreline type by its ESI number; instead, responders either ask, "Where are the marshes?" or "What is most sensitive?"

Nearly all of the existing ESI maps follow this basic 1 to 10 convention, with little variation in the assignment of ESI number by shoreline type (Table 8-2). The only exceptions are: Virginia, Maryland, and North Carolina, which have marshes ranked ESI = 7, 8, 10, and 11; Louisiana which has ESI = 1 to 7; and the Columbia River which has ESI = 1 to 6. In an automated system, the ESI rank would be part of the attribute information, along with the specific shoreline geomorphology, so that thematic maps could be made using any combination of data attributes.

Because the sensitivity mapping system will eventually be applied to most of the U.S., including coastal, lacustrine, and riverine systems, uniformity in classification, color-coding, and symbology will be of great benefit. Research on optimization of mapping colors and symbology for ESI maps is currently underway, and the results will be published in a separate report.

<u>Subtidal Habitats.</u>–In a subtidal setting, oil vulnerability of habitats is much lower because they are not likely to be directly contaminated by floating slicks. Exceptions include some sites or tidal stages when these habitats become intertidal. The sensitivity of a subtidal habitat usually derives from the species which use the habitat. Thus, kelp beds, which have not been shown to be

directly affected by oil, are nonetheless very sensitive because they provide habitat and shelter for animals which are sensitive, such as sea otters. These habitats represent whole communities which have complex interrelationships and functions. The subtidal habitats have not traditionally been ranked; rather, they have been treated more as living resources which vary in sensitivity with season and location. The approach has been to map only the subtidal habitats that have been determined to be most sensitive. In the past, mapping has covered:

- Eelgrass beds
- Submerged aquatic vegetation
- Worm reefs
- Large beds of kelp
- Coral reefs

Other subtidal bottom types have not been included. If there are other subtidal areas that are important to a specific species, those areas are designated according to the species, life stage present, and season of use, not the habitat.

Biological Resources

There are numerous animal and plant species that are potentially at risk from oil spills. Table 8-3 lists the major groups (elements) and sub-groups of species which are included on sensitivity maps. There are seven major biological elements and each element is further divided into groups of species with similar ecological behavior relative to oil spills. Each of these sub-element groups is composed of individual species that have similar oil-spill sensitivities. For example, there are eight sub-elements for birds, with raptors including those species of accipiters, falcons, and osprey which nest close to major waterbodies and feed on fish or seabirds. On the maps, the distribution of oil-sensitive fish and wildlife is mostly shown by patterns and symbols representing these ecological groupings, with annotations for each species present.

Table 8-3. Components of biological and human-use resources included on sensitivity maps

Data Element	Sub-Element	Comments
Habitats	Shoreline Types	ESI or other geomorphological class
	Eelgrass Beds/SAV	Includes all types of subtidal grass beds
	Kelp	
	Coral Reefs	
	Worm Beds	
Marine Mammals	Whales	Seasonal use areas; Migration routes
	Dolphins	Population concentration areas
	Sea Lions	Haulouts
	Seals	Haulouts
	Sea Otters	Population concentration areas
	Manatees	Population concentrations areas
	Walruses	Haulouts
	Polar Bears	
Terrestrial Mammals	Mustelids	Concentration areas
	Rodents	Concentration areas
	Deer	Intertidal-feeding species
	Bear	Intertidal feeding areas
Birds	Diving Coastal Birds	Rookeries; Forage/wintering areas
	Waterfowl	Wintering areas; Migration stopover areas
	Alcids	Rookeries; Wintering concentration areas
	Petrels/Fulmars	Rookeries
	Shorebirds	Nesting beaches; Migration stopover areas
	Wading Birds	Rookeries; Critical forage areas
	Gulls/Terns	Nesting sites
	Raptors	Nest sites; Critical forage areas
Fish	Anadromous Fish	Spawning streams
	Beach Spawners	Spawning beaches
	Kelp Spawners	
	Nursery Areas	For estuarine, demersal, pelagic fish
	Reef Fish	Includes fish using hardbottom habitats
	Special concentrations	Estuarine and demersal fish

Table 8-3. Continued

Data Element	Sub-Element	Comments
Mollusc	Oysters	Seed beds; Leased beds; Abundant beds
	Mussels	Leased beds; Abundant beds
	Clams	Harvest areas; Abundant beds
	Scallops	Harvest areas; Abundant beds
	Abalone	Harvest areas; High concentrations
	Conch/whelk	Harvest areas; High concentrations
	Squid/octopus	Harvest areas; High concentrations
Crustaceans	Shrimp	Nursery areas
	Crabs	Nursery areas; High concentration sites
	Lobster	Nursery areas; High concentration sites
Reptiles	Sea Turtles	Nesting beaches
	Alligators	Concentration areas
Recreation	Beaches	High-use recreational beaches
	Marinas	
	Boat Ramps	
	Diving Areas	
	Boating/Fishing	High-use recreational areas
	State Parks	
Management Areas	Marine Sanctuaries/National Parks	
	Refuges	
	Preserves/Reserves	Areas of special biological concern/WMA
Resource Extraction	Subsistence	Officially designated harvest sites
	Commercial Fisheries	
	Water Intakes	Industrial; Drinking water; Power plants
	Mining	Intertidal/subtidal mining leases
	Aquaculture sites	Fish/shrimp/bivalves/plants
	Log storage areas	
Cultural	Archaeological Sites	
	Native American Res.	

Note that under "Comments" on Table 8-3 is listed the types of areas which should be included. Many marine and coastal species are wide-ranging; they can be present over a very large area at any time. Maps or data indicating the entire area of occurrence of fish species, for example, can cover very large areas and thus not help responders in assessing resources at risk and protection priorities. However, natural resources are most at risk from oil spills when:

- Large numbers of individuals are concentrated in a relatively small area, such as bays where rafts of waterfowl concentrate during migration and overwintering.
- They come ashore for birthing, resting, or molting, such as seal haulouts.
- Early life stages are present in somewhat restricted areas, such as nursery areas for anadromous fish, turtle nesting beaches, and bird rookeries.
- Areas important to specific life stages or migration patterns, such as foraging or overwintering sites, are impacted by oil.
- Specific areas are known to be vital sources for seed or propagation.
- The species are threatened or endangered.
- A significant percentage of the population is likely to be exposed to oil.

Therefore, sensitivity maps show where these most sensitive species, life stages, and areas are located, not the entire area over which the species are known to occur.

Several types of distributions are shown. Point locations (in the form of latitude and longitude) are used for sites of very small areal extent, such as bird rookeries and mammal haulouts. Range bars or lines are used to show sites along a shoreline which is used for a specific activity, such as the length of a stream used for spawning by anadromous fish or the extent of a beach where turtles nest. Biological distributions which are spread over an area are shown by polygons with patterns, such as oyster seed beds, important nursery areas for estuarine fish, or high concentration waterfowl overwintering areas.

Table 8-4 lists the associated data for each element which should be included, at the species level. These data allow identification of the most sensitive periods

Table 8-4.

DATA ELEMENTS AND ASSOCIATED DATA FOR RESOURCES AT RISK
=Polygon, L=Line, *=Point)

State/Federal Endangered or Threatened species marked by *.

(S/E) = Start date/End date
(Arr.) = Arrival date

arine ammals	Lifestage Present (Adult, Adult breeder, Juvenile, Present)													Concentration			Species/	Expert Contact	Breeding		
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Count	High	Medium	Low	(*Endangered)	(Name, agency, phone)	Mating (S/E)	Calving (S/E)	Pupping (S/E)
P Whales																					
P Dolphins																					
*/P Sea lions																					
*/P Seals																					
P Sea otters																					
P Manatees																					

errestrial Mammals	Lifestage Present (Adult, Adult breeder, Juvenile, Present)													Concentration			Species/	Expert Contact
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Count	High	Medium	Low	(*Endangered)	(Name, agency, phone)
P Mustelids																		
P Rodents																		
P Deer																		
P Bear																		

rds	Lifestage Present (Adult, Adult breeder, Juvenile, Present)													Concentration			Species/	Expert Contact		Breeding		
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Count	High	Medium	Low	(*Endangered)	(Name, agency, phone)	Nesting (Arr.)	Laying (S/E)	Hatching (S/E)	Fledging (S/E)
*/P Diving Coastal birds																						
P Waterfowl																						
*/P Alcids																						
*/P Petrels/fulmars																						
*/P Shorebirds																						
*/P Wading birds																						
*/P Gulls/terns																						
*/P Raptors																						

sh	Lifestage Present (Adult, Juvenile, Larvae, Egg, Present)													Concentration			Species/	Expert Contact		Breeding
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Count	High	Medium	Low	(*Endangered)	(Name, agency, phone)	Spawning (S/E)	Outmigration (S/E)
L/P Anadromous																				
L/P Beach spawners																				
P Kelp Spawners																				
P Nursery areas																				
P Reef fish																				
P Special concentrations																				

olluscs	Lifestage Present (Adult, Juvenile, Larvae, Egg, Present)													Concentration			Species/	Expert Contact	Breeding	
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Count	High	Medium	Low	(*Endangered)	(Name, agency, phone)	Mating (S/E)	Spawning (S/E)
P Oysters																				
P Mussels																				
P Clams																				
P Scallops																				
P Abalone																				
P Conch/whelk																				
P Squid/Octopus																				

rustaceans	Lifestage Present (Adult, Juvenile, Larvae, Egg, Present)													Concentration			Species/	Expert Contact	Breeding	
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Count	High	Medium	Low	(*Endangered)	(Name, agency, phone)	Mating (S/E)	Spawning (S/E)
P Shrimp																				
P Crab																				
P Lobster																				

eptiles	Lifestage Present (Adult, Juvenile, Egg, Present)													Concentration			Species/	Expert Contact	Breeding	
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Count	High	Medium	Low	(*Endangered)	(Name, agency, phone)	Nesting (S/E)	Hatching (S/E)
L/P Sea turtles																				
P Alligators																				

Table 8-4. Continued

DATA ELEMENTS AND ASSOCIATED DATA FOR RESOURCES AT RISK

(P=Polygon,L=Line,*=Point)

ELEMENT		SUB-ELEMENT	DATA FIELDS									
Habitat												
	L/P	Shoreline type	ESI-1	ESI-2	ESI-3	ESI-4	ESI-5	ESI-6	ESI-7	ESI-8	ESI-9	ESI-10
	P	Eelgrass/SAV										
	P	Kelp										
	P	Coral reef										
	P	Worm beds										
Recreation			Name	Owner	Phone/Contact							
	L	Beaches										
	*	Marinas				# Slips	Access Capabilities					
	*	Boatramps				Size	Construction					
	P/*	Diving areas										
	P	Parks										
	P/*	Boating/fishing				Boating	Fishing	Type				
Management Areas			Name	Owner	Phone/Contact							
	P	Nat. Park/Mar. Sact.										
	P	Refuges										
	P	Preserves/reserves										
Resources Extraction			Name	Owner	Phone/Contact	Type						
	L/P	Subsistence					Season					
	P	Commercial Fishery					Season					
	*	Aquaculture					Season					
	*	Water Intakes					Depth	Volume				
	*	Mining					Active					
	L/*	Log Storage										
Cultural			Name	Owner	Phone/Contact	Type						
	*	Historical										
	*	Archeological					# Sites					
	P	Native American										

for each species and determination of protection priorities on a seasonal basis. For each species or species group, detailed information is provided on the life stage present by month of year.

For mammals and birds, life stages include adult, adult breeder, and juvenile, or just present if the life stage is unknown. Not present is indicated to differentiate from no data available. The earliest start and latest end dates for breeding activity of marine mammals and birds are used to determine the presence of eggs or young. Calving dates apply only to whales, dolphins, and manatees, whereas pupping dates apply to sea lions, seals, and sea otters. The number of individuals or breeding pairs is listed (if known); otherwise descriptive qualifiers of the number or relative size of the population likely to use the area are indicated. For example, heavily used seal haulouts can be ranked as high, whereas sites which are infrequently used can be ranked as low. Previously, information on sensitivity maps showed only presence of these animals by season; the user had to obtain numbers of animals present and life stage and breeding status from other sources or general life-history profiles. The availability of life-stage and concentration information helps planners and responders make better decisions on protection and cleanup priorities.

For terrestrial mammals, breeding information is usually not included since these data are seldom known. Rather, the life stage presence by month is used to indicate when young are likely to be present.

For fish, emphasis is placed on important spawning and rearing areas in shallow-water environments, where sensitive life stages are concentrated and at risk of exposure to high levels of oil in the water column. Therefore, shallow water and intertidal spawning areas are shown for anadromous fish, beach spawners such as grunion, and kelp spawners such as herring. The entire length of stream used for spawning by anadromous fish is shown. Nursery areas for larval and juvenile fish in estuarine settings, particularly for species of commercial or recreational importance, are highlighted. Reef and shallow hardbottom habitats are included as areas of fish concentration at risk from floating slicks. Life-stage information includes larvae and eggs, and breeding activity includes start and end dates for spawning and outmigration of fry.

Molluscs and crustaceans are always indicated as areas, designated as important seed beds, harvest areas, abundant beds, or otherwise high concentration areas. Life stages present for each month include adults, juveniles, larvae, and eggs, and breeding activity start and end dates include mating and spawning. The concentration descriptors can be used to designate relative importance of the site or area. For example, seed oyster beds would be designated as high, whereas viable but closed oyster beds would be designated as low. The objective is to provide responders with the information needed to determine protection priorities.

The only information usually shown for turtle nesting beaches is the start and end date for laying of eggs and hatching of the young. For all other life stages, turtles range widely and have no habitat preferences which increase their likelihood of encountering oil. Information for alligators is shown as areas of occurrence, with designation of life stages present, if known.

Threatened and endangered species are shown with a special flag to indicate their management status. Species on both state and federal lists are shown. It may be very important to include the expert contact for a specific resource, someone who could be contacted to provide current species status or special protection requirements. General, resource-wide contacts, such as the State Historic Preservation Office for archaeological sites, should be listed elsewhere. However, this section of the database lists the key person or agency knowledgeable about a specific resource, if there is one.

In the past, standardized symbols for each of these resources have been used, with general color patterns for major ecological groups. Symbols are used to represent important species groupings within a major group. For example, a different symbol is used for each of the eight sub-grouping under birds in Table 8-3. These symbols allow the user to readily identify the general group of organism and its general risk without having to know the specific species composition. As mentioned above for habitats, there is an on-going research effort to identify symbology and patterns for use in generation of hardcopy maps and screen views from GIS databases.

On the ESI maps, biological resource information is noted by colored circles (Fig. 8-2). The color of the circle identifies the type of organism present: yellow =

marine mammal; green = bird; orange = shellfish; blue = fish; red = reptile. Biological groups are identified by symbols within the circles (Table 8-5). Numbers in the circles refer to species or species groups listed in each atlas. Dots in the circle indicate seasonality. This information allows the prediction of species' presence or absence during a specific time of the year. A red border indicates that the species is rare, threatened, or endangered. The location and range of species are indicated by the bars and arrows that extend from the circle. Special symbols identify the approximate perimeter of kelp beds and the extent of seagrass beds.

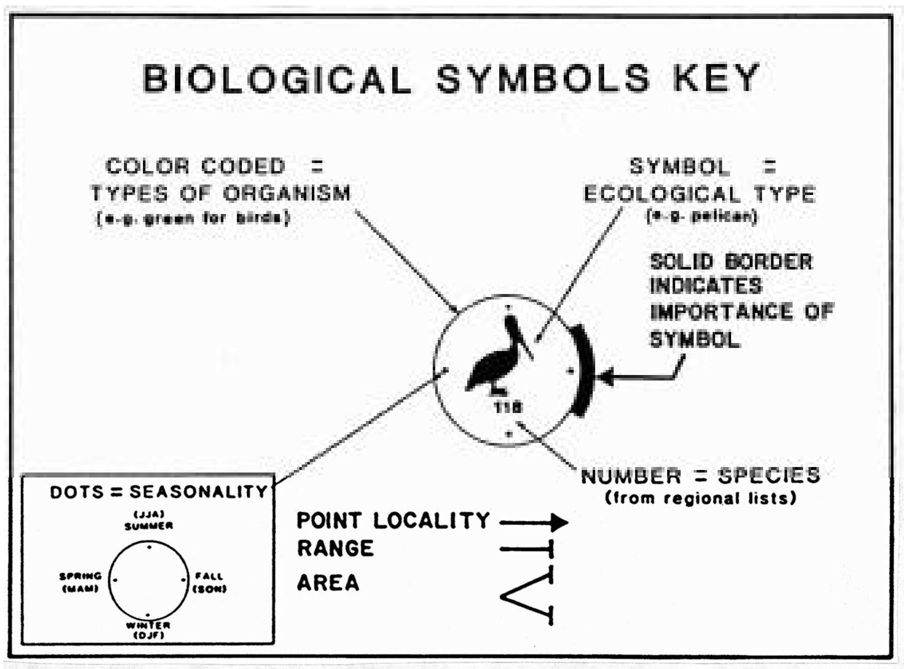

Figure 8-2. Key to information provided on colored biological markers on the ESI maps.

Areas of socioeconomic importance (major state and local parks and marinas) may support high-intensity recreational use, knowledge of which would be important to the on-scene coordinator. These areas are marked by a black decal on a white background. In addition to parks and beaches, other shoreline areas have been specially designated for scenic, wildlife, or other values. These areas include reserves, preserves, refuges, and ecological areas. They are marked by a brown circle and a star with a number keyed to the area's name and the agency with controlling authority. For the California ESI maps, approximate boundaries are given for Areas of Special Biological Significance as designated by the State Water Resources Control Board.

Table 8-5. Symbols used on the Environmental Sensitivity Index maps to indicate dominant groups in southern California.

Symbol	Occurrence
Resident Marine Mammals	
Seals or Sea Lions	Haulout grounds or pupping areas
Marine Birds	
Diving birds	Pelican or Cormorant feeding and roosting areas
Alcid or Petrels	Auklet, Guillemot, Murrelet, or Petrel rookeries
Waterfowl	Duck, Goose, or Brant forage areas
Shorebirds	Oystercatcher, Plover, Avocet, Sparrow, Rail, Stilt or Killdeer forage areas or rookeries
Gulls or Terns	Rookeries or forage areas
Fish	
Grunion or Herring	Spawning areas
Steelhead Trout	Spawning or nursery areas
Shellfish	
Clams	Clam, Scallop, or Mussel areas
Abalone	Abalone areas
Reptiles	
Turtle	Green Sea Turtle areas
Plants	
Kelp	Abundant brown algae beds
Seagrass	Subtidal eel grass beds
Socioeconomic Features	
Parks and beaches	Location
Marinas	Location
Areas of special biological significance	Boundaries
Protective Strategy Features	
Recommended boom	Location
Skimmers	Deployment
Closures	Location
Shoreline washover potential	Location

Human-Use Areas

Previously designated as socio-economic resources on ESI maps, human use areas can be divided into four major components (Table 8-3):

- High-use recreational use and shoreline access areas
- Officially designated natural resource management areas
- Marine and coastal resource extraction sites
- Close-to-shore archaeological and cultural sites

Each of these components are discussed below.

As for biological resources, recreational areas shown on sensitivity maps should include high-use recreational beaches and sport-fishing, boating, and diving areas. Shoreline parks indicate high amenity value. Boat ramps and marinas are shown, both as recreational sites and for shoreline access. Marina size (number of slips) can help set protection priorities. Name/phone contacts for marinas and parks can facilitate notification and collection of information on site suitability for shoreline access and construction details needed for operations support.

Officially designated natural resource management areas include national parks and marine sanctuaries, national wildlife refuges, wildlife management areas, preserves and reserves set aside by various agencies and organizations, and other ecological sites that have special resource management plans or status. In the event of a spill, the contact and phone number for the management area are needed for notification and inquiry as to current conditions (e.g., number/species of waterfowl actually present or expected in the near future). Likewise, contact information for water intakes and aquaculture sites (including exact location, depth of intake, use, volume, presence of alternative sources) is critical.

Where appropriate, log storage sites and intertidal/subtidal mining leases are included so that appropriate protection and cleanup strategies can be developed. Each has a unique problem or issue which can significantly complicate oil removal strategies. Log storage sites can contain large numbers of valuable wood products, which, when oiled, must be cleaned at great expense prior to sale. Owners of intertidal mining leases must be contacted before removal of oiled sediment can begin. For each site, the boundary, owner/user contact, and type of activity should be provided.

High-value commercial fishing areas are a very critical component, particularly leased shellfish beds and near-shore, shallow-water fisheries such as crabbing, shrimp harvest, lobster harvest, and estuarine fisheries. Many times the concern is to minimize impacts to the catch and fishing equipment as gear is pulled from the water through surface slicks. For each area, the boundary, species being utilized, time of use, and data on catch for that area should be provided. Non-commercial seafood harvest areas, including subsistence use areas, identify sites where monitoring of seafood quality may be needed to protect local populations in the event of a spill.

The most sensitive type of archaeological sites are those that are actually located in the intertidal zone, such as parts of Alaska where subsidence exposes important sites to coastal erosion. Also, sites located very close to the shoreline where they may be crossed by response or cleanup crews should be shown. The type and status (e.g., on National Register) of each site should be included. If there are multiple sites in a general area, then the area and number of sites should be indicated. Site-specific information for some highly sensitive or important archaeological resources may need to be restricted in distribution to prevent unnecessary site visits by the curious, as well as destruction by vandals. In such a case, then the general area of the sites should be designated and a contact for access to specific location information and methods of protection provided.

How Sensitivity Maps are Used

Contingency Planning

Integral to the prespill planning process is the designation of protection priorities for selected spill scenarios so that site-specific protection equipment requirements can be identified. These priorities, as determined by local, area, and/or regional planning committees, are derived from analysis of the resources at risk. Preplanning also includes development of shoreline cleanup strategies, based on the shoreline type and use.

Sensitivity maps play an extremely important role in training and the development of credible spill scenarios. In particular, seasonal differences in resource presence and sensitivity can be significant, altering the resources at risk, protection priorities, and appropriate response and cleanup activities. For example, the presence of early life stages of commercially important fish and shellfish species in the water column usually precludes the use of dispersants in the vicinity. However, in the winter, when large numbers of waterfowl are concentrated in nearshore waters, dispersant use might be a viable means to reduce bird impacts. Cleanup priorities are often driven by the seasonal arrival of a species or sensitive life stages, such as concentrating efforts to remove oil from turtle nesting beaches prior to the arrival of nesting turtles. Just the physical disturbances of cleanup activities have been shown to disrupt nesting success of birds, so setting exclusion dates for cleanup activities by species can significantly affect cleanup planning and scheduling.

Preplanning is made more powerful with access to an automated system; just being able to generate maps at various scales increases the power of planning. Very detailed maps are needed for site-specific protection strategies and equipment pre-staging. In contrast, maps of sensitive resources are oftentimes better presented in overview for analysis of risks and priorities. For example, the need, type, and location of bird rescue operations in Puget Sound is best determined by analysis using maps of nesting colonies and waterfowl concentration areas for the entire Sound, with symbols and patterns representing relative size and species sensitivity. *Ad hoc* querying by the user for any combination of resource information is needed for automated systems. Thus, unique, non-interfering symbology is critical, and this is very difficult to achieve for all the ranges of possible combinations.

Spill Response

When the initial notification of an actual or potential spill is received, ESI maps are consulted to determine what resources are likely to be present and their relative risks to impacts from exposure to oil. Having all the resource information on one set of maps, addressing oil spills, greatly facilitates this resources-at-risk assessment. The maps are multi-disciplinary, allowing quick evaluation of the potential magnitude of the spill's impact, based on the initial information on the spill and the general trajectory of the slick. Only if such data have been compiled onto one set of maps can they be quickly used to support time-critical decisions, such as the use of chemical agents to disperse the slick or where are the most important sites for exclusion booming.

Once the area of impact is more defined, the resource information is used to create spill-specific sensitivity maps (based on impact area and season). These spill-specific maps are distributed to response personnel in the field and command posts for incorporation into response strategies and determination of protection priorities. These maps are be used to identify potential bird and mammal impacts so that appropriate rescue and cleanup actions can be planned. Resource managers for the impacted areas are contacted to verify the species and numbers of animals actually present and to determine specific response strategies.

As the response moves from establishing priorities to developing cleanup criteria, sensitivity maps are used to determine the need and limitations of shoreline cleanup techniques. Used in conjunction with degree-of-oiling maps, summary maps and statistics can be generated to show the areas proposed for various treatment methods, or the percent of a shoreline type proposed for treatment. Exclusion zones can be plotted for certain types of cleanup activities; for example, exclusion zones for aircraft above bird rookeries and marine mammal haulouts during nesting and pupping season can be plotted on maps for distribution to pilots. The location of exclusion booms can be shown on maps for distribution to boaters, to show areas which they should avoid.

In the future, determination of resources at risk and protection strategies during oil spills will be assisted by the development of GIS applications with automated mapping functions. State and federal agencies are using GIS technology for management of natural resource information, and applications for oil spill planning and response are planned in many states. Automation brings many powerful tools to the spill response community and managers of natural resources. However, a word of caution. The role and benefit of automated sensitivity mapping in spill response may be overvalued–too much may be expected too soon, and there are many complex issues that need to be resolved. Furthermore, it will take years to digitize the data. However, GIS technology will facilitate the generation of thematic maps for specialized planning requirements and preparation of maps at various scales. It should be noted that the primary analytical products of an oil spill GIS are still maps, which are distributed to many types of users. GIS technology provides the ability to analyze complex spatial data trends and display the results in a powerful geographical format. However, the tough decisions still must be made in an environment where conditions rapidly change and systems may not be able to keep up with the pace.

Chapter 9.
Glossary of Oil Spill Terms

acute
Having a sudden onset, lasting a short time. Can be used to define either the exposure or the response to an exposure (effect). The duration of an acute aquatic toxicity test is generally 4 days or less and mortality is the response measured (Rand and Petrocelli 1985).

arcuate
A bowed or curved delta with the convex margin facing the body of water; also known as fan-shaped delta.

aromatic hydrocarbon
Carbon-hydrogen compounds characterized by the presence of at least one six-carbon ring structure.

bbl
Barrel, a unit of liquid volume for petroleum products. Equivalent to 42 gallons.

bioaccumulation
A general term describing a process by which chemicals are taken up by aquatic organisms from water directly or through consumption of food containing the chemicals (Rand and Petrocelli 1985).

bioassay
A test used to evaluate the relative potency of a chemical by comparing its effect on a living organism with the effect of a standard preparation of the same type of organism (Rand and Petrocelli 1985).

biodegradation
The breakdown of organic compounds by microorganisms.

biomagnification
The result of the process of bioaccumulation by which tissue concentrations of bioaccumulated chemicals increase as the chemical passes up through two or more trophic levels (Rand and Petrocelli 1985).

cetacean
The group of wholly aquatic mammals that includes whales and dolphins.

chronic
Involving a stimulus that is lingering or continues for a long time; often signifies periods from several weeks to years, depending on the reproductive life cycle of the aquatic species. Can be used to define either the exposure or the response to an exposure (effect). The chronic aquatic toxicity test is used to study the effects of continuous, long-term exposure of a chemical or other potentially toxic material on aquatic organisms (Rand and Petrocelli 1985).

cuspate
A crescent-shaped bar joining with the shore at both ends.

depuration
A process that results in the elimination of a material from an aquatic organism.

emphysema
A pulmonary disorder characterized by overdistension and destruction of the air spaces in the lungs.

eucaryotic
Organisms possessing nucleated cells, essentially all organisms except bacteria or viruses.

gneiss
A variety of rocks with a banded or coarsely foliated structure formed by regional metamorphism.

hydrophobic
Lacking an affinity for, repelling, or failing to adsorb or absorb water.

hypoglycemia
Abnormally low levels of glucose in the blood.

LC_{50}
Concentration of any toxic chemical that kills 50 percent of the organisms in a test population per unit time.

lipophilic
Having an affinity for, attracting, or the ability to adsorb or absorb lipids (fats).

metabolite
Any substance involved in or a product of metabolism.

mysid

Planktonic shrimp-like crustaceans that carry their young in a pouch; hence, the common name "opposum shrimp."

mysticete
The baleen whales.

NOAA
National Oceanic and Atmospheric Administration

NOEC
No observed effect concentration, the highest dosage of a compound administered in a toxicity test that does not produce toxic effects. Also called no observed effects level, or NOEL.

nominal concentration
In chemical or toxicological studies with oil, the concentration of a compound expressed as total oil mixed per unit volume water (as opposed to oil concentration in the water phase).

OSC
Federal On-Scene Coordinator

OSHTF
Oil Spill Health Task Force, an interagency group formed to address issues of seafood contamination and human health implications during the *Exxon Valdez* oil spill.

ordered population
A population is ordered if the elements within the population are ordered in magnitude according to some scheme (Scheaffer et al. 1986).

orogeny
The process of mountain formation, especially the intense deformation of rocks by folding and faulting which, in many mountainous regions, has been accompaniedb y invasion of molten rock and volcanic eruption.

osmoregulatory mechanism
Any physiological mechanism for the maintenance of an optimal and onstant level of osmotic activity of the fluid in and around the cells.

PAH
Polycyclic aromatic hydrocarbons

population or universe
Refers to the entire collection of measurements about which one wishes to draw conclusions (Zar 1984).

random population
A population is random if the elements of the population are in random order (Scheaffer et al. 1986).

SSC
NOAA Scientific Support Coordinator, one of the OSC's Special Forces designated in the National Contingency Plan.

surfactant
Surface active agent, a soluble compound that reduces the surface tension of liquids, or reduces interfacial tension between two liquids of a solid.

toxicity
"The inherent potential or capacity of a material to cause adverse effects in a living organism" (Rand and Petrocelli 1985).

trophic level
Any of the feeding levels through which the passage of energy through an ecosytem proceeds; examples are photosynthetic plants herbivorous animals, and microorganisms of decay.

organoleptic
The detection of contamination of food items through smell or taste.

ppm
Parts per million, a measurement of concentration. Can also be expressed in units of weight, for example, as milligrams/kilogram (mg/kg) or micrograms/gram (μg/g)

pinniped
the group of marine mammals that includes seals, walruses, and sealions.

tainting
The development of flavors or odors in foods that are not typical of the food itself.

toxicity index
The concept of toxicity evaluation in which toxicant concentration and toxicant exposure time are considered to be equal factors in resultant toxicity. Expressed as a product of the day, as in ppm days or ppm hours.

zoospore
Motile, flagellated asexual reproductive cell in protozoans, algae, and fungi.

10 Appendices

Case Histories

Santa Barbara Channel Oil Spill: Spill Summary

On 28 January 1969, a Union Oil drilling platform offshore of Montecito had a blow-out. Oil was released from the well at various rates for several weeks. On February 16, Union Oil placed the first steel hood to accumulate the oil. Over 3.3 million gallons have been estimated to have been released. Nearly 1.3 million gallons had come ashore by 8 February, contaminating over 160 km of shoreline. There was a period of very heavy rainfall during the spill, with reports by divers of oily debris sinking at the fresh water/suspended sediment plume contact with salt water. Dispersants were used for over a year, with 25,080 gallons used in March 1969. Heavy oil slicks covered large areas of kelp. Straw was widely used as a sorbent.

Lessons learned

- Although large amounts of oil were held in the kelp beds for weeks, the oil did not adhere to healthy vegetation. No oil was observed in diving surveys beneath the kelp or on the bottom.
- Most of the oil was removed from the beach within months by winter storms.
- Some oil was buried on depositional sand beaches, but was removed by the following November.
- Oiled straw was much more persistent than oiled sediments.
- It was hypothesized that some oil sank when it came in contact with high loads of suspended sediments.
- Impacts to marine mammals were very small; no impacts to whales or elephant seals, but some mortality of sea lions which was not proven to be related to the spill.
- Large numbers of seabirds were affected, with little success at rehabilitation.

- Most surprisingly, very little damage was observed to intertidal organisms and no direct impacts to fish (although the commercial fishery was impacted).

References

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Kolpack, R.L. 1971. Physical, chemical,and geological studies, Volume II: Biological and oceanographical survey of the Santa Barbara Channel oil spill 1969-1970. Sea Grant Pub. No. 2. Los Angeles: Allan Hancock Foundation, Univ. S. Calif. 477 pp.

Arrow Spill, Chedabucto Bay, Nova Scotia: Spill Summary

The tanker *Arrow* ran aground on 4 February 1970, spilling about 3 million gallons of Bunker C fuel oil. Over 300 km of shoreline were contaminated. Storm waves drove the oil into the water column, both during the spill and as the oil was eroded off the beaches. This particulate oil persisted for over three months, and it was incorporated by copepods into fecal pellets. As much as 10 percent of the oil in the water column was associated with the copepods, and 7 percent was found in the fecal pellets. Extensive mechanical cleanup of gravel beaches was conducted, including removal of oiled sediments. Impacts to intertidal communities were locally severe. In sheltered areas, oiled sediments were highly persistent, and, five years later, high levels of oil were found in clams but not mussels or algae. Oiled pavements remain in sheltered areas as of 1991.

Lessons learned

- Heavy oils can be transferred to bottom sediments via uptake by copepods which then pass the oil with fecal material to the bottom.
- Natural removal of oil from high-energy shorelines occurred quickly, with only small amounts of tar remaining in sheltered microenvironments.

- In sheltered shorelines, asphalt pavements, buried oil layers, and contaminated interstitial water can persist for over twenty years.
- Removal of oiled gravel can result in increased beach and cliff erosion.
- Long-term impacts to intertidal communities are associated with persistent oiled sediments, with lower bivalve recruitment rates, lower species diversities, lower shell growth rates for clams, and dieback of brown algae still detectable six years after the spill.

References

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Conover, R.J. 1970. Some relations between zooplankton and Bunker C oil in Chedabucto Bay following the wreck of the tanker Arrow. J. Fish. Res. Board Canada, Vol. 28, pp. 1327-1330.

Exxon Valdez, Prince William Sound, Alaska

Summary

On March 24, 1989, the tanker *Exxon Valdez*, en route from Valdez, Alaska, to Los Angeles, California, grounded on Bligh Reef in Prince William Sound, Alaska. Eleven tanks were torn open in the grounding, spilling an estimated 11 million gallons of Prudhoe Bay crude oil.

Cleanup operations began almost immediately, and continued at varying levels of effort over the next two and a half years (and may not be entirely completed). In 1989, the treatments embraced a range of methods that included skimming, booming, manual pickup, wiping, and tilling, high-pressure hot-water washing, bioremediation, and tests of a number of other mechanical and chemical methods. In 1990, manual pickup, berm relocation tilling, and bioremediation were the principal methods employed. In 1991, pickup, berm relocation tilling, and bioremediation continued at a much reduced group of sites that showed evidence of significant oiling.

In July of 1990, a cooperative interagency research project was begun to evaluate the effects of oiling and treatment on the biological communities of the intertidal zone, and to study the course of recovery from both. Designed as a long-term monitoring effort, the program has continued into 1991 and beyond. Original funding sponsors of the project included NOAA, the U.S. EPA, the U.S. Coast Guard, and the American Petroleum Institute/Minerals Management Service. Exxon USA provided vessel and aircraft logistics in 1990. In 1991, the Marine Spill Response Corporation also became a sponsor, while Exxon withdrew completely. The intent was to create a long-term monitoring program to track recovery and differences in rates of recovery among sites that had received different degrees of oiling and treatment, with the ultimate goal of providing guidance as to the ecological effects of treatment methods.

Results of observations

- Significant differences were noted among sites that were a) oiled and hot water washed, b) oiled and not hot water washed, and c) unoiled. At sites where hot water washing was employed, important representatives of the intertidal community were missing or seriously depleted.
- While evidence of bioaccumulation was noted in some intertidal organisms, particularly mussels, there was no evidence of biomagnification through the food web.
- Although eelgrass studies showed adverse impacts related to oiling in 1990, by 1991 such differences were not observable.
- By 1991, most areas showed signs of recovery being well underway. However, the sites that had experienced the most severe treatments in 1989 were still obviously retarded in the extent of recovery noted. In addition, some intrusively treated sites that appeared normal from the perspective of algal cover showed a severely altered animal community structure relative to less harshly treated sites.

Lessons learned

- High pressure hot water washing can be effective in mobilizing stranded oil so that at least some can be recovered from the shoreline. However, the temperatures and pressures typically used in such operations result in a wide range of adverse biological impacts, from sterilization of the treated intertidal zone to movement of oil residues from one zone to another.

- Although negative biological impacts were observed to have resulted from both oiling and intrusive shoreline treatment, those attributable to treatment predominated. At the most severely treated locations, only minimal signs of recovery were evident in fall of 1991.
- However, at most oiled sites, the process of recovery appeared to be well underway in 1991.
- Limited evidence suggests that it may be possible to mediate the adverse impacts of washing by reducing both temperature and pressure of the water. Areas where such judgement was used show lesser degree of impact than those where 140° high pressure washing was used.
- It is very important to monitor and document as accurately as possible the extent of oiling on shorelines, and the treatments that take place. Lack of detailed information on both of these seriously hinder subsequent evaluation of recovery.
- If a monitoring program is to be established, it is very important to designate areas where no treatment is to take place. However, it may be very difficult to obtain consensus on this, particularly in highly visible, heavily utilized, or heavily populated areas.

Texaco Refinery Spill, Fidalgo Bay, Washington

Summary

During a tanker offloading operation on February 22, 1991, a shoreside booster pump failed at the Texaco March Point refinery. A large piece of the pump casing broke and was thrown 90 feet, and North Slope crude oil began pouring from the pump. The oil flowed across a field and into a drainage ditch, and ultimately oil entered Fidalgo Bay through two culverts. 210,000 gallons of oil were estimated to have spilled, with approximately 20-30,000 gallons entering Fidalgo Bay.

Fidalgo Bay is a relatively small and shallow embayment in northern Puget Sound near the city of Anacortes, Washington. It is characterized by a broad mud flat intertidal area, and large subtidal eelgrass beds. The shoreline surrounding Fidalgo Bay, although it includes fringing marsh vegetation, is not exactly a pristine environment: much of the area was diked and filled for agricultural purposes in the late 1800s and early part of this century, and presently, a state highway borders two sides of the bay.

In an effort to keep the oil from contaminating the extensive eelgrass beds and the herring spawn that was associated with it at the time of the spill, the oil that was present along the shore was effectively boomed in, preventing it from moving into the offshore eelgrass beds but holding it against portions of the shoreline and variably contaminating part of the fringing marsh. The spill took place during an unusually high tide series and oil reached portions of the shoreline only occasionally flooded.

Skimming operations took place on the water, while on the shoreline, a number of different cleanup methods were employed. Some rubble substrate that had been oiled was removed and replace with clean substrate, to minimize oil exposure to smelt that use the area for spawning. Other areas were hand wiped to remove visible oil. Heavily oiled portions of the marsh/shoreline were vacuumed using vacuum trucks. Where possible, low pressure ambient temperature seawater was used to lift oil in conjuction with vacuuming. Lightly oiled areas were raked with pom pom material. Pom pom-type booms were strung along the shoreline to capture oil that seeped or was flushed into the water.

In April, in order to evaluate the progress of recovery in the marsh, NOAA began a simple program of monitoring the chemistry and biology of the marsh area, and sampling visits have continued on a regular basis since then. The sampling program has consisted primarily of monthly photographs of a series of 0.25 m^2 quadrats established in oiled and unoiled areas, and chemistry collections of marsh sediments. Samples for analysis of below-ground biomass were collected during the initial visit and will likely be collected on an annual basis.

Results of observations

- Chemical analyses of the most heavily impacted portions of the shoreline indicated that the weathering of the North Slope crude oil began at a slow rate relative to that observed in the initial weeks of the Exxon Valdez spill. However, the rate in Fidalgo Bay accelerated significantly during the warm months of July and August.

- Marsh plants were relatively dormant until June, when noticeable growth occurred at both oiled and unoiled sites. Growth continued through September.
- Areas with heaviest amounts of oil remaining on the surface showed little or no growth of marsh plants. However, areas with moderate amounts of oil had steady growth through the growing season.
- Areas that were subjected to the most foot traffic have been among the slowest to recover.

Lessons learned

- Even simple qualitative projects can yield useful insights into how areas recover from environmental insults and how treatment can affect the process of recovery.
- Removal of spilled oil in marshes resulting in relatively low biological impacts is possible under certain circumstances that are related to the physical and biological characteristics of the marsh, the intrusiveness of the remedial technique, the season of the year, and other considerations.
- Removal of the oil has apparently speeded the recovery of those portions of the marsh where it occurred.
- Techniques to minimize the impacts of foot traffic and equipment access resulted in significantly lesser adverse effects on the recovery of the marsh.
- However, minimization of impacts required near constant vigilance and threat of financial discomfort.