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Vulnerability of Coastal Environments to Oil Spill Impacts

Erich R. Gundlach and Miles O. Hayes
University of South Carolina

Contingency planning for potential oil spills is becoming a necessity for most of the coastal waterways of the United States. An important part of a usable contingency plan is the protection of those coastal environments most likely to be seriously damaged by oil contamination in the event of a spill.

On the basis of field studies of five major oil spills and a review of the literature, major coastal environments have been classified on a scale of 1 to 10 in terms of potential vulnerability to oil spill damage. The scale emphasizes oil residence time, with consideration of initial biological impacts. Exposed rocky headlands and wave-cut platforms (1 and 2 on the Vulnerability Index) are generally least affected by an oil spill. Coarse-grained sandy and gravel beaches, which are subject to oil penetration and burial, are assigned intermediate index values of 4 to 7. Sheltered environments such as sheltered rocky coasts, salt marshes, and mangroves (index values of 8 to 10) are the environments most likely to be adversely affected by oil spills. For example, residence times of over 10 years are predicted for some salt marsh areas.

INTRODUCTION

Oil spill contingency plans are rapidly becoming commonplace on both regional and local levels in response to public concern for the environment. A well-developed contingency plan involves: (1) delineation of possible spill sources and subsequent dispersal patterns; (2) selection of boom, oil recovery and disposal sites; (3) determination of proper spill clean-up and control methods; and (4) a coordinated and well-organized system of rapid response to any oil spillage. An integral part of this effort is the determination of which coastal environments would be most seriously damaged by an oil spill so that they may receive priority protection. This report introduces a classification of coastal environments in terms of potential vulnerability to oil spill damage and suggests suitable methods of response to oil contamination for each. A rapid means for determining environmental type and applying the classification is also presented.

The necessity for oil spill contingency planning has been brought to national attention by the rash of oil related accidents occurring between 15 December 1976 and 15 February 1977. Included on this list is the wreck of the *Argo Merchant* (7,700,000 gallons;[1] the largest tanker spill to occur in U.S. waters); the explosion of the tanker *Sansinena* in Los Angeles (9 killed, 50 injured); and a series of other spills in the Thames River, Connecticut; Delaware River, Pennsylvania; Hudson River, New York; and in Buzzards Bay, Massachusetts.[2] Oil transport related incidents (tanker accidents, off-loading to shore facilities, and normal ship operations) account for more than one-third of the estimated 6.1 million metric tons of oil that enter the marine environment annually.[3] Tanker accidents are clearly the most visible source of oil contaminants, and at the center of public awareness concerning oil spills.

Since 1971, the United States Coast Guard has been responsible for the collection and analysis of data concerning the occurrence, location and size of oil spills within U.S. territory.[4] During 1974, there were 11,440 reported oil pollution incidents of which vessel activity accounted for 26% of the total number of incidents, and 25% of the 15,802,000 gallons lost.[5] Oil loss from marine facilities accounted for another 6% of the incidents and 8% of the total volume lost. Coastal waters experienced a full 70% of the oil-related incidents, while inland waters accounted for an additional 20% of the total. Since 1971, there has been a 52% increase in the reported number of oil discharges and an 83% increase in the volume of oil lost. The increased dependence of the United States on imported oil can only lead to more tanker accidents and resultant environmental damage. Prior planning against oil spills, undertaken at critical locations, can help to minimize the potential disaster.

On-site study of a number of oil spills (Table 1) by our research group (Oil Spill Assessment Team, University of South Carolina) has enabled direct observation of the reaction and response of a variety of different coastal environments to oil impact. Studies of the *Metula* oil spill site (one, one-and-a-half, and two years after the spill) showed varying quantities of oil on mixed sand and gravel beaches, exposed tidal flats, and protected marshes.[6,7,8] The *Urquiola* oil spill in northwestern Spain affected exposed and protected rocky coasts, marshes, tidal flats, and fine and coarse-grained recreational beaches.[9,10,11] The *Jakob Maersk* spill contaminated exposed and protected sandy beaches and rocky coasts.[12] Spillages from the oil barges *Bouchard* #65[13,14] and the *Ethel H.*[15] illustrated ice-oil interactions such as might be expected from spills occurring under arctic conditions. At each spill, except the *Metula,* clean-up was attempted, with widely varying results. From these studies and analysis of the literature, the following classification scheme has been developed.

PROPOSED CLASSIFICATION

Coastal environments are classified on a scale of 1-10 in terms of potential vulnerability to oil spill damage. This scale is called the Vulnerability Index and is summarized in Table 2. Vulnerability is based on shoreline interaction with the physical processes controlling oil deposition, observed persistence or longevity of the oil in that environment, and the extent of biological damage. Total prediction of biologic response to oil contamination is extremely difficult. Among other factors,[3] reaction will vary with the type and amount of oil spilled, season,[16,17] life stage of the organism,[18,19] and length of exposure to the contaminant.[20] Therefore, the presented biological information is only general and should be supplemented with field data gathered during study of the contingency plan area. The environments covered in our classification are listed below in order of increasing vulnerability to oil spill damage.

1. Exposed steeply dipping or cliffed rocky headlands:

Exposed rocky headlands are common along the eastern shore of North America in northern New England and Nova Scotia and along the Pacific Coast from Baja California to Alaska. Most areas of this type are exposed to high wave energy. Oncoming waves forcefully reflect back off the rock scarps, usually generating a return flow. In the event of an oil spill, this return flow would keep most of the oil off the rocks. This process was observed at several localities during the *Urquiola* oil spill in Spain. The exposed portions of the rocky coast escaped oil damage entirely. Studies in Bermuda[21] showed that tar from numerous spill incidents similarly did not have a chance to stick to vertical slopes along the coast due to constant wave action. In addition, the great mixing action associated with the swash zone at the base of the rocks aids in the natural breakdown of the oil into smaller particles which are more easily degraded by bacteria. Oil spill control and clean-up is usually unnecessary on these coasts because of the low level of contamination and rapid rate of natural clean-up.

2. Eroding wave-cut platforms:

These areas consist of narrow wave-swept beaches in front of eroding glacial material (as along the north shore of Long Island) or platforms cut directly into crystalline or sedimentary rock which may be covered with sand or gravel (as along the Californian and Alaskan coasts). Wave action is usually high, and a natural cleansing of the beach occurs rapidly, generally within weeks. At the *Metula* oil spill site, areas of this type were entirely cleared of oil by the time of our first site visit one year after the spill. The rate of oil removal is a function of wave climate; the greater the wave energy, the more rapidly will oil be removed. In most cases, oil spill clean-up or control methods are not necessary.

3. Flat, fine-grained sandy beaches:

Fine-grained beaches (0.0625-0.25 mm grain size) usually have a flat profile and are hardpacked, such as Daytona Beach, Florida, where cars are able to drive over the beach. Indigenous biota generally consist of mollusks (e.g. surf clams), infauna (especially amphipods) and meiofauna (organisms <0.05 mm which live in the interstitial water between sand grains). Several studies have indicated that damage to these organisms is severe during an oil spill.[22,23,24] Our observations during the *Urquiola* spill support this contention. At several of the heavily oiled, fine-grained beaches, thousands of dead amphipods were found along the high tide swash line. However, although initial biological damage may be great, repopulation of the beach may occur within a year,[22,23] depending on the extent and longevity of the oil and inherent properties of the ecosystem.[18]

Physical clean-up of the oil is aided by the close packing of the grains on a fine-sand beach, which effectively inhibits oil penetration to less than a few centimeters below the surface. A thin layer of oil on the surface can often be readily scraped off by a motorized scraper. Under heavy oil accumulations, the most efficient method calls for use of the motorized scraper in conjunction with a motorized elevator scraper.[25] Caution must be taken (1) to wait until all oil is on the beach, (2) to not repeatedly drive over the oiled portions (further grinding the oil into the beach), and (3) to remove only minimal quantities of sand. Long-term beach erosion

TABLE 1

Oil Spills Studied by OSAT*

Oil Spill	Date	Type & Amount of Oil	Affected Coastline	Control/Treatment Methods	OSAT Field Studies
Metula, Strait of Magellan, Chile	Aug. 1974	Type: Saudi Arabian Crude 3% Bunker C 53,000 tons total 40,000 tons on coastline	150 km, sand and gravel beaches; estuaries; marshes/ tidal flats	No clean-up or control activities	12-20 Aug. 1975 4 Feb. - 13 Mar. 1976 12-23 Aug. 1976
Urquiola, La Coruña, Spain	May 1976	Type: Persian Gulf Crude 2% Bunker C 110,000 tons total, 25-30,000 ashore	215 km; sandy beaches; rocky shores; estuaries; marshes/tidal flats	Dispersants Booms and pumps Heavy machinery Manual labor	17 May - 10 June 1976
Jakob Maersk, Porto, Portugal	Jan. 1975	Type: Iranian Crude 2% Bunker C 80,000 tons total, 15-20,000 ashore	Sandy beaches; rocky shores; shore facilities	Dispersants Booms Heavy machinery Manual labor	4-6 June 1976
Bouchard #65, Wings Neck Area Buzzards Bay, Mass., US	Jan. 1977	Type: No. 2 fuel oil; 275 tons	Approx. 1-2 kms; fast ice; protected beaches	Suction pumps Sorbents	30 Jan. - 3 Feb. 1977
Ethel H, Lower Hudson R., New York, US	Feb. 1977	Type: No. 6 fuel oil; 1500 tons lost	10 km of shoreline; little apparent damage due to fast ice along shoreline	Booms Ice skimmer (Suction truck on LCM)	7-8 Feb. 1977
OBSERVER STATUS					
Argo Merchant, 17 miles off Nantucket Is., US	Dec. 1976	Type: No. 6 fuel oil; 27,000 tons	None	Rough sea conditions prevented effective use of control equipment	Overflight 23 Dec. 1976
Ekofisk Platform; North Sea 140 miles SW of Norway	Apr. 22-30 1977	Type: North Sea crude 22,000 tons lost	None	Skimmer and booms rather ineffective	25-30 Apr. 1977

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*Oil Spill Assessment Team, Coastal Research Division, University of South Carolina.

TABLE 2

Summary of Proposed Environmental Classification in Order of Increasing Vulnerability to Oil Spill Damage

Vulnerability Index	Shoreline Type	Comments
1	Exposed rocky headlands	Wave reflection keeps most of the oil off-shore. No clean-up is necessary.
2	Eroding wave-cut platforms	Wave swept. Most oil removed by natural processes within weeks.
3	Fine-grained sand beaches	Oil doesn't penetrate into the sediment, facilitating mechanical removal if necessary. Otherwise, oil may persist several months.
4	Coarse-grained sand beaches	Oil may sink and/or be buried rapidly making clean-up difficult. Under moderate to high energy conditions, oil will be removed naturally within months from most of the beachface.
5	Exposed, compacted tidal flats	Most oil will not adhere to, nor penetrate into, the compacted tidal flat. Clean-up is usually unnecessary.
6	Mixed sand and gravel beaches	Oil may undergo rapid penetration and burial. Under moderate to low energy conditions, oil may persist for years.
7	Gravel beaches	Same as above. Clean-up should concentrate on the high-tide swash area. A solid asphalt pavement may form under heavy oil accumulations.
8	Sheltered rocky coasts	Areas of reduced wave action. Oil may persist for many years. Clean-up is not recommended unless oil concentration is very heavy.
9	Sheltered tidal flats	Areas of great biologic activity and low wave energy. Oil may persist for years. Clean-up is not recommended unless oil accumulation is very heavy. These areas should receive priority protection by using booms or oil sorbent materials.
10	Salt marshes and mangroves	Most productive of aquatic environments. Oil may persist for years. Cleaning of salt marshes by burning or cutting should be undertaken only if heavily oiled. Mangroves should not be altered. Protection of these environments by booms or sorbent material should receive first priority.

may become a serious problem if excessive amounts of sand are removed. Manual raking may prove adequate and less costly for removing light to moderate oil accumulations.

4. Steeper, medium- to coarse-grained sand beaches:

These beaches (0.25-2.0 mm grain size) are present in a variety of coastal environments, varying from low energy beaches along the Gulf Coast, to higher energy environments along the Atlantic and Pacific Coasts. Biological activity is relatively low and generally not a major consideration. Oncoming oil may readily sink 15-25 cm into the sand and be buried by natural processes to much greater depths. At Playa de Doniños, Spain, a high wave energy beach impacted by the *Urquila* spill, oil was buried in discontinuous layers 50.100 cm below the surface of the beach within a few days after initial oil impact.

Oil spill clean-up becomes very difficult when oil is buried deep in the beach. Complete removal of all oil-contaminated sediment could result in long-term damage to the beach. As an additional problem, heavy machinery can easily become trapped and immobilized in the loosely packed sand. Fortunately, the same high energy beach processes that caused rapid oil burial will also remove most of the oil from the beachface, within a relatively short period of time, usually weeks to months. However, the use of machinery may be necessitated to remove oil deposited above normal wave action during high spring or storm tides and on beaches with lesser wave action.

5. **Exposed, compacted tidal flats:**

These are compacted, fine-grained (either mud or sand) tidal flats that are relatively exposed to winds, waves and currents. As observed at the *Metula* and *Urquiola* spill sites, oil does not readily adhere to, nor penetrate into, the compacted surface of these flats. Most of the oncoming oil is readily moved over the surface of the tidal flat and onto the beach at its edge. Any oil remaining on the flat will be degraded rapidly by natural processes. Biological activity is fairly extensive, consisting mostly of infaunal organisms (mainly polychaete and nematode worms and mollusks). Though most of the oil does not remain on the surface of the flat, moderate to heavy oil concentrations may severely dmage the indigenous biological community. If necessary, clean-up activities should concentrate on the manual removal of possible small oil pools left after each tidal cycle. Machinery should be used only if the oil coverage becomes very extensive.

6. **Mixed sand and gravel beaches:**

Beaches of this type are common in New England, Nova Scotia and Alaska and are often located in moderate to high energy environments. Oil readily penetrates 10-20 cm into the sediment, and burial may be rapid, possibly within a few days. The biological community of the beachface is relatively limited due to the instability of the environment. Oil spilled on this type of beach may remain for long time periods. At the *Metula* site, oil deposited high on the beach during spring tides was still present two years after the spill. In addition, removal of all the oil can be extremely difficult without further damaging the beach. Under most circumstances, it would probably be best to let natural processes eliminate the oil on the beachface and concentrate mechanical or manual labor on the removal of oil deposited at the upper edge of the high tide swash zone.

7. **Gravel beaches:**

Gravel beaches (>2 mm grain size) commonly occur along the coasts of New England, Nova Scotia and the Pacific Northwest. Oil penetrates rapidly and deeply into the coarse sediments of this beach type. At Playa de Canabal in Spain, crude oil from the *Urquiola* seeped 60-80 cm into the fine gravel beach. Lighter, processed oils would probably penetrate even further. In addition, oil may be buried rapidly by shifting gravel under high wave energy conditions. A moderately to heavily-oiled gravel beach is practically impossible to clean without removal of large amounts of sediment which may result in possible adverse effects to the long-term stability of the beach. In the 12 months following removal of coarse sediment oiled by the *Arrow* spill in Chedabucto Bay, Nova Scotia, the beach at Indian Cove retreated between 10 and 20 m.[26] Major biological activity, which is usually limited to the sublittoral zone, may be extensive and diverse. Sinking or dispersed oil may cause long-term damage to the bottom community.[27]

8. **Sheltered rocky coasts:**

The numerous coves and protected embayments along the rocky coastline of the North American West Coast and that of northern New England and Nova Scotia are representative of this type. Oil will coat the rough surfaces and tidal pools found within this environment. The longevity of oil spill damage is influenced by the degree of wave activity.[17] In more exposed areas, oil will be degraded fairly rapidly; whereas in very protected environments, oil could remain for years. The resident biological community, consisting of algae, mollusks, crustaceans, infauna, etc. is extensive, varied and vulnerable to oil spill damage.

Clean-up is equally difficult and very expensive since this environment is usually relatively inaccessible. The use of dispersants, steam, sand blasting, scraping or almost any other method, only increases the amount of biological damage. Only if an area is inundated with heavy oil concentrations should clean-up be considered.

9. **Sheltered estuarine tidal flats:**

Protected tidal flats are common within estuaries and lagoons along the Atlantic, Pacific and Gulf coasts. Biological productivity is usually high, consisting of large populations of mollusks and polychaete worms. Oil spilled in this coastal type may have long-term deleterious effects. Estuarine environments in Falmouth, Massachusetts[28] and Penobscot Bay, Maine[29] remained adversely affected years after each received minor oil pollution. As a result of the *Urquiola* oil spill in Spain, 70% of the edible cockle population on a protected, sandy tidal flat was destroyed.[9] In addition, removal of the oil contaminant is impossible without further destroying the area and resident biological community. During an oil spill, efforts should concentrate on preventing oil from entering this environment by using booms[30] and oil absorbent materials.[31]

10. **Sheltered estuarine salt marshes and mangrove coasts:**

Marshes are among the most productive of all aquatic environments.[32,33] A vast variety of organisms and plants live in delicate balance with the environment. It is the spawning ground for a large number of sport and commercial fish. Detritus from the marsh provides an important food source for many marine organisms. Oil contamination may persist with detrimental effects for years.[34] Heavy oil accumulations from the supertanker

Metula showed essentially no change after two years within a *Salicornia* marsh system on the south shore of the Strait of Magellan. Based on the apparently slow rate of oil degradation, we estimate that oil will remain in this environment for at least ten years. During a single spill of lesser concentration, the marsh has a better chance of relatively rapid recovery.[16] The likelihood of causing long-term damage increases with successive spillages.[35]

Mangroves occur commonly along the Gulf Coast and Caribbean shorelines. As with salt marshes, mangroves contain an extensive and diverse ecosystem and play an important role in the oceanic food chain.[36] Oil contaminants can have negative long-term effets on the mangrove community. Oil from the tanker *Zoe Colocotronis* caused the defoliation and death of 1 hectare of red and black mangroves in southwest Puerto Rico over the three years following the spill.[37] Death may have been caused by oil residues in the soil and oil on the prop roots. In the Florida Keys oil spill, red mangroves sustaining more than 50% oiling of their leaves were killed.[38] Black mangroves having more than 50% oiling of their pneumatophores, or being located in oily sediment, also died. During the *Witwater* spill off Panama in 1968, it was the mangroves that suffered the most damage of all the oil affected coastal environments.[24] Recovery of a mangrove ecosystem takes an estimated minimum of 20 years.[36] Though the number of studied oil-affected mangrove systems is not great, the variety and extent of its biological community, its vulnerability to pollutants,[36] as well as the difficulty in removing oil residues from the extensive root system of the mangrove, places this environment at the upper end of our classification scheme.

Salt marshes and mangrove shorelines should be delineated as part of the contingency plan and designated as the primary environments to receive protection upon the occurrence of an oil spill. Booms or sorbent material should be applied to prevent oil from entering these areas. In extreme cases, such as occurred during the *Urquiola* spill, booms may be utilized to trap oil within one area to prevent it from spreading to other, previously unspoiled shorelines. Once a salt marsh is severely contaminated, burning or cutting has been suggested, but should be undertaken only as a last resort.[39-41] Some studies indicate that cutting has been used effectively in a number of instances,[42,43] though study of plant regeneration in untreated areas was not made. Flushing of the oiled marsh with water under low pressure is presented as the biologist's choice of methods in reference,[41] since burning or cutting will result in almost total destruction of the resident benthic community. In applying any of these methods, it must be realized that, often, the greatest long-term damage to the marsh is inflicted by heavy machinery and the large numbers of untrained people brought into the marsh to clean it. In most cases, and particularly where tidal action or seasonal plant growth is great, physical marine processes should be allowed to naturally cleanse the marsh.

Coral Reefs

Coral reefs are an integral part of the coastal zone ecology in tropical waters. Within United States territory, the Florida Keys, Puerto Rico and the Virgin Islands all contain extensive reef communities. The question of the extent of damage coral reefs undergo as a result of oil spills is as yet unresolved. Laboratory studies have indicated that corals vary in sensitivity to oil pollution[44-48] and can be adversely affected by certain dispersants.[44,45] Field studies in areas of oil spillage have not found resultant damage to coral reefs.[38,49] The extent of possible damage is dependent on reef depth,[38,47] the toxicity of the spilled oil and the total amount lost. Corals either exposed (as at spring low tides) or near the surface would suffer the greatest damage. Oil within coral environments probably should be left untreated except where accumulations are exceedingly heavy. More field studies are needed to resolve the question of vulnerability of coral reefs to oil spill impacts. Tentatively, they should be placed around 7-8 on the Vulnerability Index.

APPLYING THE VULNERABILITY INDEX

In order to apply the Vulnerability Index to a specific coastal area, the distribution of coastal environments must first be mapped. A rapid technique has previously been developed by Hayes and associates to determine the geomorphic variation of large sections of coast.[50] This technique, called the *zonal method,* has been applied to the southern coast of the Gulf of St. Lawrence,[51] southeastern Alaska,[50] and during study of the *Metula, Urquiola* and *Jakob Maersk* oil spills (Table 1). A modified form of the zonal method, presented below, has been applied to determine oil vulnerable environments in New England[52] and Lower Cook Inlet, Alaska.[53,54] In the study of Lower Cook Inlet, a total of 1216 km of coast was classified within 21 days by a team of three persons. Field work for the entire shoreline of New England was completed with equal rapidity.

The method consists of the following:

1. Study of available literature, aerial photographs, maps and charts of the entire area precedes field work.

2. Field work begins with an aerial reconnaissance of the entire area. Initial flights are flown at low tide to obtain maximum exposure of the intertidal zone. Observations are recorded verbally on tape and photographically with a hand-held 35 mm camera.

3. A sampling interval is selected for ground studies of all coastal environments observed during the flight. The sampling interval depends on the desired detail of the study. Areas of particular economic or ecologic importance are selected for further study.

4. Each sampling station includes:

a) a beach topographic profile run from the back beach to beyond the low water line.

b) three equally-spaced sediment samples collected from the intertidal zone (to 15 cm depth) for later grain size analysis.

c) biologic sampling of major floral and faunal groups.

d) a hand-drawn sketch made to force inspection of all aspects of the area.

e) photographs taken from various angles to illustrate morphologic and sedimentary features.

f) additional samples and trenches, as required, to determine sedimentary variation within the study area.

5. In addition to the basic study, short-term projects, such as mapping of major features within representative areas, may be undertaken.

6. Sediment samples are analyzed for size characteristics. Statistical parameters of grain size are calculated for each sample.[55] Point counts on thin sections may be made of specifically selected samples to determine composition.

7. The data is compiled, and the coast is geomorphically classified and mapped as indicated by the example provided in Figure 1A and Table 3.

8. The last stage is the construction of detailed maps indicating the determined vulnerability of each coastal environment. Calculations of the relative proportion of each coastal division to the total amount of coastline, are a convenient way of presenting the data (e.g. 32% of the coastline consists of areas 7-10 on the Vulnerability

TABLE 3

Shoreline Morphology for the Hypothetical Coastline Indicated in Figure 1. This method of data presentation is useful for rapid assessment of the coastal geomorphology of the selected study area.

SHORELINE MORPHOLOGY

A. Erosional Shorelines (32% of the total)

Subclasses	Total Shoreline (km)	% of Total Shoreline	Vulnerability Index
A1. Cliffs>30 m high with wave cut platform	15	19	1-2
A2. Cliffs<30 m high with wave cut platform	6	8	1-2 (4%) 7-8 (4%)
A3. Eroding bank of inlet channel	4	5	3-4

B. Neutral Shorelines (39% of total)

Subclasses	Total Shoreline (km)	% of Total Shoreline	Vulnerability Index
B1. Mountainous with steep high scarps	5	7	7-8
B2. Hilly lowlands with low scarps	4	5	1-2
B3. Protected fine sand beaches	9	12	3-4
B4. Coarse sand beaches	6	8	3-4
B5. Mixed sand and gravel beaches	2	3	5-6
B6. Pocket gravel beaches	3	4	7-8

C. Depositional Shorelines (29% of total)

Subclasses	Total Shoreline (km)	% of Total Shoreline	Vulnerability Index
C1. Arcuate delta	1	1	3-4
C2. Beach ridges	2	3	3-4
C3. Recurved spit	1	1	3-4
C4. Bay mouth bar	1	1	3-4
C5. Sand tidal flat	3	4	5-6
C6. Mud tidal flat	5	7	9-10
C7. Salt marsh	9	12	9-10

Index and should receive priority protection). A hypothetical coast and its classification (modeled after the *Urquiola* oil spill site) is presented in Figure 1B.

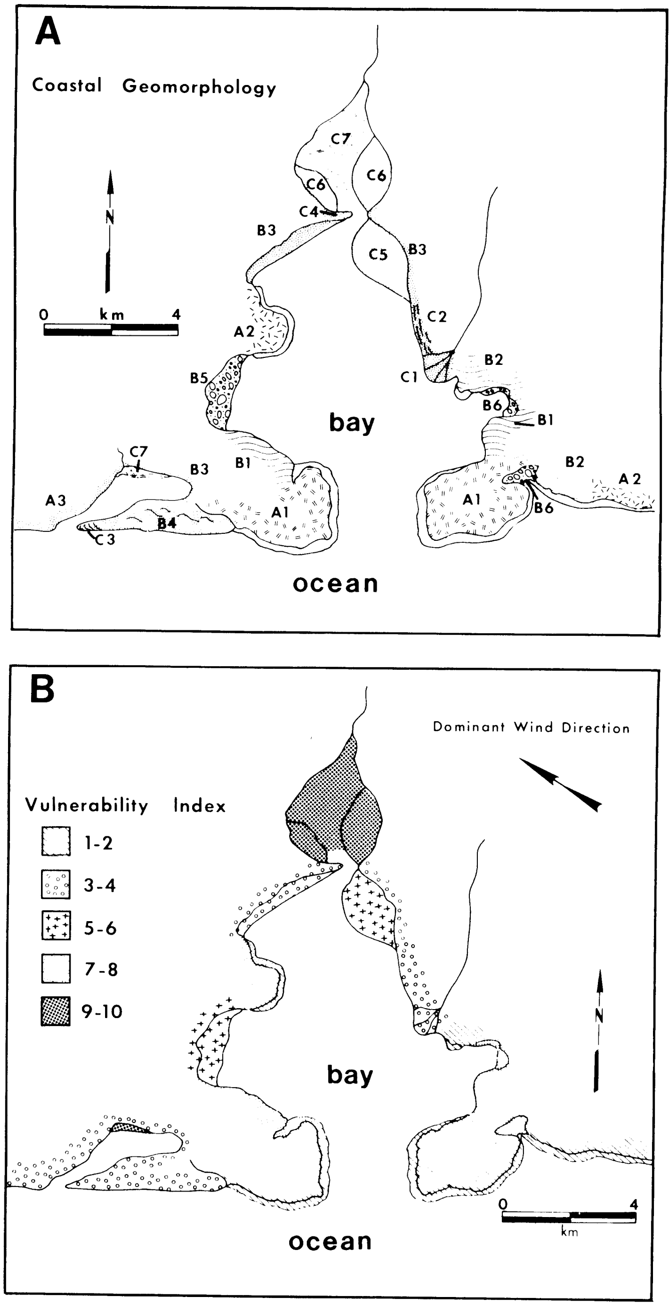

Figure 1. A. Coastal geomorphology of a hypothetical shoreline. Shoreline types (A1-B6) are listed in Table 3.

B. Application of the Vulnerability Index to the shoreline types of Fig. 1A. In this model, 28% of the shoreline is classified as having a VI = 1-2, 31% has a VI = 3-4 (low risk areas), 7% has a VI = 5-6, 15% has a VI = 7-8, and 19% is classified as high potential oil spill damage with a VI = 9-10.

Oil exploration or related shore facilities would be best positioned in the lower part of the bay, away from the highly vulnerable estuarine system (C6-C7) at the head of the bay.

CONCLUSIONS

The combination of the modified *zonal method* of rapid assessment of coastal environments and the application of the oil spill Vulnerability Index (VI) denoting the potential vulnerability of those environments to oil spill damage is an effective, rapid, and relatively low cost method of providing baseline information to coastal managers and others concerned with planning against oil spills. Areas classified as being most vulnerable to oil spill damage (VI = 8-10) include marshes, mangroves, tidal flats, and protected rocky environments. Coral reefs are possibly highly vulnerable, but field data are lacking to verify that conclusion. Exposed rocky cliffs and wave cut platforms are least likely to be damaged (VI = 1-2). Within the intermediate category (VI = 3-7) are beaches of various grain sizes and exposed tidal flats. Priority protection and treatment should be extended to those environments most likely to be damaged by oil. Assessment of the region's biologic character and influential physical processes (winds, currents, tides, etc.) should accompany the geomorphic Vulnerability Index study to give the coastal manager or oil spill contingency planner the maximum amount of information concerning the coastal environments, spill trajectories and areas of economic and ecologic importance.

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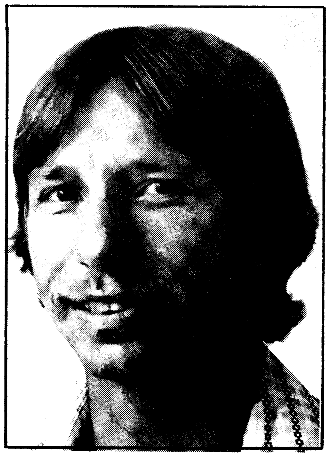
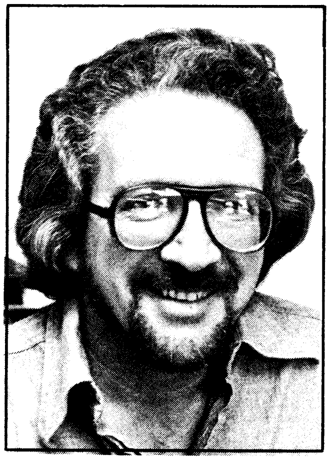


Erich R. Gundlach is a Ph.D. graduate student in the Geology Department at the University of South Carolina. As part of the Coastal Research Division—Oil Spill Assessment Team, he has been involved with the investigation of oil spill impact on the coastal zone since August 1975. He has participated in studies of the *Metula, Urquiola, Jakob Maersk,*and *Ethel H.* (Hudson River) oil spills. Before these activities, he was a member of the Peace Corps assigned to the School of Fisheries, Food Sciences and Oceanography at the Catholic University of Valparaiso, Chile. He received his Master's Degree in an environmentally related Earth Science program at the University of New Hampshire.



Miles O. Hayes is Professor of Geology and Director of the Coastal Research Division at the University of South Carolina. He received his Ph.D. from the University of Texas. He has published over 50 scientific articles, books and reports relating to the coastal zone. Recently, he has conducted field research on coastal processes and geomorphology in South Carolina, Alaska and Kuwait, in addition to studies of oil spills in Chile, Spain and Portugal.