many of these ongoing endeavors are profitable, high-value products such as biopharmaceuticals, biopigments, and pearls will need to be advanced to realize the full potential of the deep water.

The cold sea water may have applications for open-ocean mariculture. Artificial upwelling of deep water has been suggested as a method of creating new fisheries and marine biomass plantations. Should development proceed, open-ocean cages can be eliminated and natural feeding would replace expensive feed, with temperature and nutrient differentials being used to keep the fish stock in the kept environment.

Agriculture

An idea initially proposed by University of Hawaii researchers involves the use of cold sea water for agriculture. This involves burying an array of cold water pipes in the ground near to the surface to create cool weather growing conditions not found in tropical environments. In addition to cooling the soil, the system also drip irrigates the crop via condensation of moisture in the air on the cold water pipes. Demonstrations have determined that strawberries and other spring crops and flowers can be grown throughout the year in the tropics using this method.

Energy Carriers

Although the most common scenario is for OTEC energy to be converted into electricity and delivered directly to consumers, energy storage has been considered as an alternative, particularly in applications involving floating plants moored far offshore. Storage would also allow the export of OTEC energy to industrialized regions outside of the tropics. Long-term proposals have included the production of hydrogen gas via electrolysis, ammonia synthesis, and the development of shore-based mariculture systems or floating OTEC plant-ships as ocean-going farms. Such farms would cultivate marine biomass, for example, in the form of fast-growing kelp which could be converted thermochemically into fuel and chemical co-products.

See also

Carbon Dioxide (CO_2) Cycle. Geophysical Heat Flow. Heat and Momentum Fluxes at the Sea Surface. Heat Transport and Climate.

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OIL POLLUTION

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Introduction

This article describes the sources of oil pollution, composition of oil, fate when spilt, and environmental effects. The initial impact of a spill can vary from minimal to the death of nearly everything in a particular biological community, and recovery times can vary from less than one year to more than 30 years. Information is provided on the range of effects together with the factors which help to determine the course of events. These include oil type and volume, local geography, climate and season, species and biological communities, local economic and amenity considerations, and clean-up methods. With respect to clean-up, decisions sometimes have to be made between different, conflicting environmental concerns. Oil spill response is facilitated by pre-spill contingency planning and assessment including the production of resource sensitivity maps.

Oil: a High Profile Pollutant

Consider some of the worst and most distressing effects of an oil spill: dying wildlife covered with oil; smothered shellfish beds on the shore; unusable amenity beaches. It is not surprising that ever since the *Torrey Canyon* in 1967 (the first major tanker accident) oil spills have been media events. Questions about environmental effects and adequacy of response arise time and time again, but to help answer these it is now possible to draw upon decades of experience from three main types of activity: post-spill case studies and long-term monitoring; field experiments to test clean-up methods; and laboratory tests to investigate toxicities of oils and dispersants.

Oil is a complex substance containing hundreds of different compounds, mainly hydrocarbons (compounds consisting of carbon and hydrogen only). The three main classes of hydrocarbons in oil are alkanes (also known as paraffins), cycloalkanes (cycloparaffins or naphthenes) and arenes (aromatics). Compounds within each class have a wide range of molecular weights. Different refined products ranging from petrol to heavy fuel oil obviously differ in physical properties such as boiling range and evaporation rates, and this is related to the molecular weights of the compounds they contain. Crude oils are also variable in their chemical composition and physical properties, depending on the field of origin. Chemical and physical properties are factors which partly determine environmental effects of spilt oil.

Tanker Accidents Compared With Chronic Inputs

Tanker accidents represent a small, but highly visible, proportion of the total oil inputs to the world's oceans each year (**Figure 1**). The incidence of large tanker spills has, however, declined since the 1970s. Irrespective of accidental spills, background hydrocarbons are ubiquitous, though at low concentrations. Water in the open ocean typically contains 1–10 parts per billion but higher concentrations are found in nearshore waters. Sediments or organisms may accumulate hydrocarbons in higher concentrations than does water, and it is common for sediments in industrialized bays to contain several hundred parts per million.

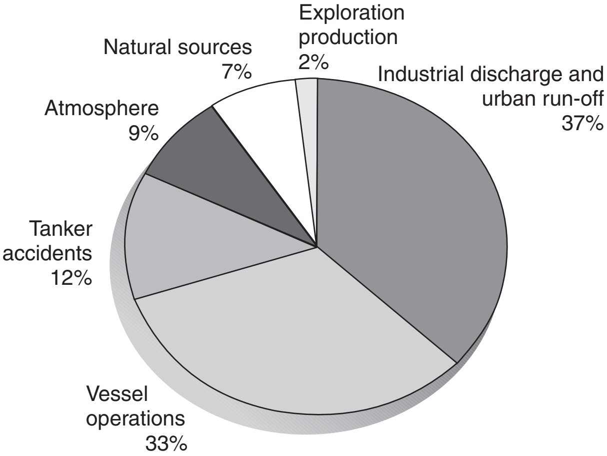

Figure 1 Major inputs of oil to the marine environment.

Sources of background hydrocarbons include:

- Operational discharges (e.g. bilge water) from ships and boats;
- Land-based discharges (e.g. industrial effluents, rainwater run-off from roads, sewage discharges);
- Natural seeps of petroleum hydrocarbons, such as occur, for example, along the coasts of Baffin Island and California;
- Airborne combustion products, either natural (e.g. from forest fires) or artificial (e.g. from the burning of fossil fuels);
- Organisms, e.g. leaf waxes and hydrocarbons synthesized by algae.

Notwithstanding the relatively great total amounts of oil from operational and land-based sources these discharges usually comprise diluted, dissolved and dispersed oil. The sections below focus on accidental spills because it is these which produce visible slicks which may coat wildlife and shores, and which typically require a clean-up response.

Natural Fate of Oil Slicks

When oil is spilt on water, a series of complex interactions of physical, chemical, and biological processes takes place. Collectively these are called 'weathering'; they tend to reduce the toxicity of the oil and in time they lead to natural cleaning. The main physical processes are spreading, evaporation, dispersion as small drops, solution, adsorption onto sediment particles, and sinking of such particles. Degradation occurs through chemical oxidation (especially under the influence of light) and biological action – a large number of different species of bacteria and fungi are hydrocarbon degraders. Case history evidence gives a reasonable indication of natural cleaning timescales in different conditions. For open water sites, half-lives (the time taken for natural removal of 50% of the oil from the water surface) typically range from about half a day for the lightest oils (e.g. kerosene) to seven days or more for heavy oils (e.g. heavy fuel oil). However, for large spills near coastlines, some oil typically is stranded on the shore within a few days; once oil is stranded, the natural cleaning timescale may be prolonged. On the shore observed timescales range from a few days (some very exposed rocky shores) to more than 30 years (some very sheltered shores notably salt marshes). It is estimated that natural shore cleaning may take several decades in extreme cases.

Shore cleaning timescales are affected by factors including:

- exposure of the shore to wave energy (**Figure 2**) from very exposed rocky headlands to sheltered tidal flats, salt marshes and mangroves. This in turn depends on a number of variables that include fetch; speed, direction, duration and frequency of winds; and open angle of the shore;
- localized exposure/shelter – even on an exposed shore, cracks, crevices, and spaces under boulders can provide sheltered conditions where oil may persist;
- steepness/shore profile – extensive, gently sloping shores dissipate wave energy;
- substratum – oil does not easily penetrate fine sediments (especially if they are waterlogged) unless they have biological pores such as crab and worm burrows or root holes (**Figure 3**). Penetration of shingle, gravel and some sand beaches can take place relatively easily, sometimes to depths of more than one metre;
- clay-oil flocculation – this process (first noticed on some Alaskan shores after the *Exxon Valdez* spill) reduces adherence of oil to shore substrata and facilitates natural cleaning;
- height of the stranded oil on the shore – oil spots taken into the supratidal zone by spray can persist for many years, conversely, oil on the middle and lower shore is more likely to be removed by water action. It is common to have stranded oil concentrated in the high tide area;
- oil type, e.g. viscosity affects movement into and out of sediment shores.

Oil Spill Response

Aims

The aims of oil spill response are to minimize damage and reduce the time for environmental recovery by:

- guiding or re-distributing the oil into less sensitive environmental components (e.g. deflecting oil away from mangroves onto a sandy beach) and/or

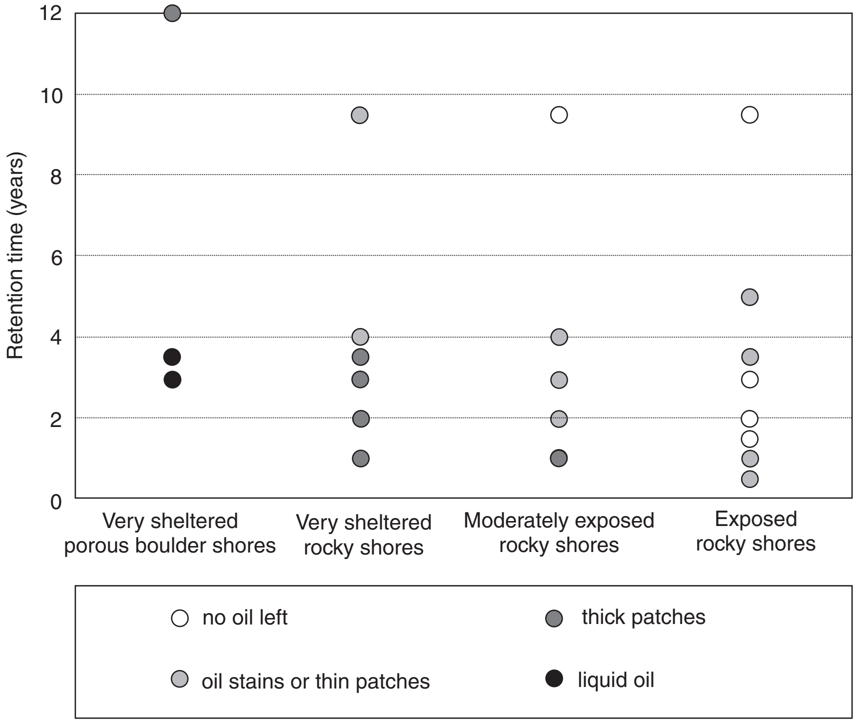

Figure 2 Oil residence times on a variety of rocky shores where no clean up has been attempted.

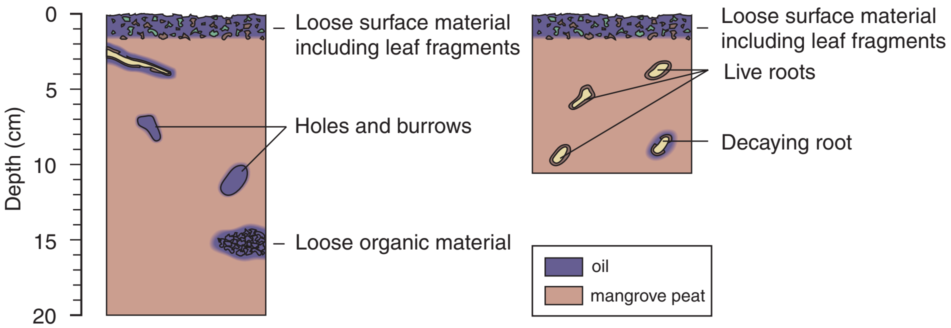

Figure 3 Two core samples taken from a mangrove swamp, showing penetration of oil down biological pathways.

- removing an appropriate amount of oil from the area of concern and disposing of it responsibly.

Initiation of a response, or decision to stop cleaning or leave an area for natural clean-up, needs to be focused on agreed definitions of 'how clean is clean', otherwise there is no yardstick for determining whether the response has achieved the desired result.

The main response options are described below.

Booms and Skimmers

Booms and skimmers can be successful if the diversion and containment of the oil starts before it has had too much time to spread over the water surface. Booms tend to work well under calm sea conditions, but they are ineffective in rough seas. When current speeds are greater than 0.7–1.0 knots (1.3–1.85 km h^{-1}), with the boom at right angles to the current the oil is entrained into the water, passes under the boom and is lost. In some cases it may be possible to angle the boom to prevent this. Booms can also be used for shoreline protection, for example to stop oil from entering sheltered inlets with marshes or mangroves. The time available for protective boom deployment depends on the position and movement of the slick, and can vary from hours to many days. The efficiency of skimmers depends on the oil thickness and viscosity, the sea state and the storage capacity of the skimmer. Skimmers normally work best in sheltered waters. Because of their limitations, recovering 10% of the oil at a large spill in open seas is considered good for these mechanisms.

Dispersants

Dispersants, which contain surfactants (surface active agents), reduce interfacial tension between oil and water. They promote the formation of numerous tiny oil droplets and retard the recoalescence of droplets into slicks. They do not clean oil out of the water, but can improve biodegradation by increasing the oil surface area, thereby increasing exposure to bacteria and oxygen. Information about dispersant effectiveness from accidental spills is limited for various reasons, such as inadequate monitoring and the difficulty of distinguishing between the contributions of different response methods to remove oil from the water surface. However, in at least some situations dispersants appear to remove a greater proportion of oil from the water surface than mechanical methods. Moreover, they can be used relatively quickly and under sea conditions where mechanical collection is impossible. Dispersants, however, do not work well in all circumstances (e.g. on heavy fuel oil) and even for initially dispersable oils, there is only a short 'window of opportunity', typically 1–2 days, after which the oil becomes too weathered for dispersants to be effective. The main environmental concern is that the dispersed oil droplets in the water column may in some cases affect organisms such as corals or fish larvae.

In situ Burning

Burning requires the use of special fireproof containment booms. It is best achieved on relatively fresh oil and is most effective when the sea is fairly calm. It generates a lot of smoke and as with dispersants, the window of opportunity is short, typically a few hours to a day or two, depending on the oil type and the environmental conditions at the time of the spill. When it is safe and logistically feasible, *in situ* burning is highly efficient in removing oil from the water surface.

Nonaggressive Shore Cleaning

Nonaggressive methods of shore cleaning, methods with minimal impact on shore structure and shore organisms, include:

- physical removal of surface oil from sandy beaches using machinery such as front-end loaders (avoiding removal of underlying sediment);
- manual removal of oil, asphalt patches, tar balls etc., by small, trained crews using equipment such as spades and buckets;
- collection of oil using sorbent materials (followed by safe disposal);
- low-pressure flushing with seawater at ambient temperature;
- bioremediation using fertilizers to stimulate indigenous hydrocarbon-degrading bacteria.

In appropriate circumstances these methods can be effective, but they may also be labor-intensive and clean-up crews must be careful to minimize trampling damage.

Nonaggressive methods do not work well in all circumstances. Low-pressure flushing, for example, is ineffective on weathered firmly adhering oil on rocks; and bioremediation is ineffective for subsurface oil in poorly aerated sediments.

Aggressive Shore Cleaning

Aggressive methods of shore cleaning, those that are likely to damage shore structure and/or shore organisms, include:

- removal of shore material such as sand, stones, or oily vegetation together with underlying roots and mud (in some cases the material may be washed and returned to the shore);
- water flushing at high pressure and/or high temperature;
- sand blasting.

In some cases these methods are effective at cleaning oil from the shore, e.g. hot water was more effective than cold water for removing weathered, viscous *Exxon Valdez* oil from rocks. However, heavy machinery, trampling and high-pressure water all can force oil into sediments and make matters worse.

Net Environmental Benefit Analysis for Oil Spill Response

In many cases a possible response to an oil spill is potentially damaging to the environment. The public perception of disaster has sometimes been heightened by headlines such as ‘Clean-up makes things worse’. The advantages and disadvantages of different responses need to be weighed up and compared both with each other and with the advantages and disadvantages of entirely natural cleaning. This evaluation process is sometimes known as net environmental benefit analysis. The approach accepts that some response actions cause damage but may be justifiable because they reduce the overall problems resulting from the spill and response.

Example 1 Consider sticky viscous fuel oil adhering to rocks which are an important site for seals. If effective removal of oil could only be achieved by high-pressure hot-water washing or sand blasting, prolonged recovery times of shore organisms such as algae, barnacles and mussels might be accepted because the seals were given a higher priority. A consideration here and in similar cases is that populations of wildlife species are likely to be smaller, more localized, and slower to recover if affected by oil than populations of abundant and widespread shore algae and invertebrates.

Example 2 Consider a slick moving over shallow nearshore water in which there are coral reefs of particular conservation interest. The slick is moving towards sandy beaches important for tourism but of low biological productivity. Dispersant spraying will minimize pollution of the beaches, but some coral reef organisms may be damaged by dispersed oil. From an ecological point of view, it is best not to use dispersants but to allow the oil to strand on the beaches, from where it may be quickly and easily cleaned.

Effects and Recovery

Range of Effects

The range of oil effects after a spill can encompass:

- physical and chemical alteration of habitats, e.g. resulting from oil incorporation into sediments;
- physical smothering effects on flora and fauna;
- lethal or sublethal toxic effects on flora and fauna;
- short- and longer-term changes in biological communities resulting from oil effects on key organisms, e.g. increased abundance of intertidal algae following death of limpets which normally graze the algae;
- tainting of edible species, notably fish and shellfish, such that they are inedible and unmarketable (even though they are alive and capable of self-cleansing in the long term);
- loss of use of amenity areas such as sandy beaches;
- loss of market for fisheries products and tourism because of bad publicity (irrespective of the actual extent of the tainting or beach pollution);

- fouling of boats, fishing gear, slipways and jetties;
- temporary interruption of industrial processes requiring a supply of clean water from sea intakes (e.g. desalination).

The extent of biological damage can vary from minimal (e.g. following some open ocean spills) to the death of nearly everything in a particular biological community. Examples of extreme cases of damage following individual spills include deaths of thousands of sea birds, the death of more than 100 acres of mangrove forest, and damage to fisheries and/or aquaculture with settlements in excess of a million pounds.

Extent of damage, and recovery times, are influenced by the nature of the clean-up operations, and by natural cleaning processes. Other interacting factors include oil type, oil loading (thickness), local geography, climate and season, species and biological communities, and local economic and amenity considerations. With respect to oil type, crude oils and products differ widely in toxicity. Severe toxic effects are associated with hydrocarbons with low boiling points, particularly aromatics, because these hydrocarbons are most likely to penetrate and disrupt cell membranes. The greatest toxic damage has been caused by spills of lighter oil particularly when confined to a small area. Spills of heavy oils, such as some crudes and heavy fuel oil, may blanket areas of shore and kill organisms primarily through smothering (a physical effect) rather than through acute toxic effects. Oil toxicity is reduced as the oil weathers. Thus a crude oil that quickly reaches a shore is more toxic to shore life than oil that weathered at sea for several days before stranding. There have been cases of small quantities of heavy or weathered oils stimulating the growth of salt marsh plants (**Figure 4**).

Geographical factors which have a bearing on the course of events include the characteristics of the water body (e.g. calm shallow sea or deep rough sea), wave energy levels along the shoreline (because these affect natural cleaning) and shoreline sediment characteristics. Temperature and wind speeds influence oil weathering, and according to season, vulnerable groups of birds or mammals may be congregated at breeding colonies, and fish may be spawning in shallow nearshore waters.

Vulnerable Natural Resources

Salt marshes Salt marshes are sheltered 'oil traps' where oil may persist for many years. In cases where perennial plants are coated with relatively thin oil films, recovery can take place through new growth from underground stems and rootstocks. In extreme cases of thick smothering deposits, recovery times may be decades.

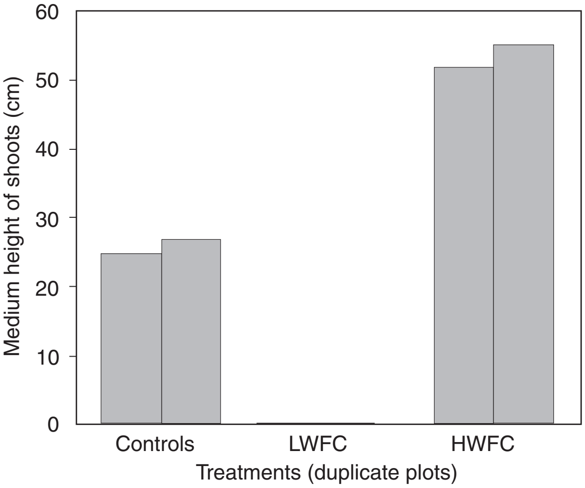

Figure 4 The effects of experimental oil treatments (duplicate plots) on shoot heights of the common salt marsh grass *Spartina anglica*. The measurements shown were taken four months after treatment. Lightly weathered Forties crude (LWFC) killed most of the grass shoots. Heavily weathered Flotta crude (HWFC) stimulated growth.

Mangroves Mangrove forests are one of the most sensitive habitats to oil pollution. The trees are easily killed by crude oil, and with their death comes loss of habitat for the fish, shellfish and wildlife which depend on them. Mangrove estuaries are sheltered 'oil trap' areas into which oil tends to move with the tide and then remain among the prop roots and breathing roots, and in the sediments (**Figure 5**).

Coral reefs Coral reef species are sensitive to oil if actually coated with it. There is case-history evidence of long-term damage when oil was stranded on a reef flat at low tide. However, the risk of this type of scenario is quite low – oil slicks will float over coral reefs at most stages of the tide, causing little damage. Deep water corals will escape direct oiling at any stage of the tide.

Fish Eggs, larvae and young fish are comparatively sensitive but there is no definitive evidence which suggests that oil pollution has significant effects on fish populations in the open sea. This is partly because fish can take avoiding action and partly because oil-induced mortalities of young life stages are often of little significance compared with huge natural losses each year (e.g. through predation). There is an increased risk to some species and life stages of fish if oil enters shallow near-shore waters which are

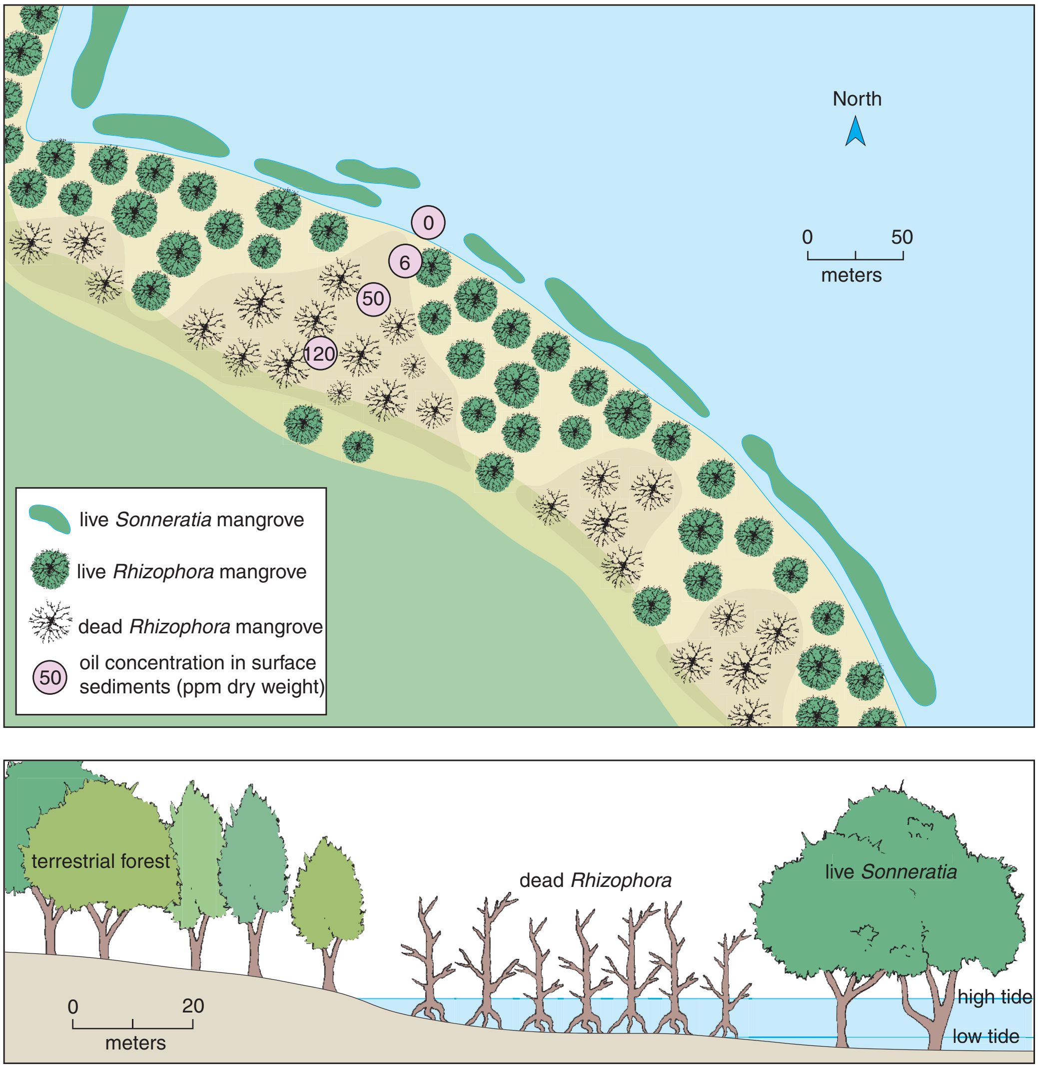

Figure 5 Plan and profile showing mangrove patches killed by small oil slicks.

fish breeding and feeding grounds. If oil slicks enter into fish cage areas there may be some fish mortalities, but even if this is not the case there is likely to be tainting. Fishing nets, fish traps and aquaculture cages are all sensitive because adhering oil is difficult to clean and may taint the fish.

Turtles Turtles are likely to suffer most from oil pollution during the breeding season, when oil at egg-laying sites could have serious effects on eggs or hatchlings. If oiling occurs, the effects from the turtle conservation point of view could be serious, because the various turtle species are endangered.

Birds Seabirds are extremely sensitive to oiling, with high mortality rates of oiled birds. Moreover, there is experimental evidence that small amounts of oil transferred to eggs by sublethally oiled adults can significantly reduce hatching success. Shore birds, notably waders, are also at risk. For them, a worst-case scenario would be oil impacting shore feeding grounds at a time when large numbers of migratory birds were coming into the area.

Mammals Marine mammals with restricted coastal distributions are more likely to encounter oil than wide-ranging species moving quickly through an area. Species at particular risk are those which rely on fur for conservation of body heat (e.g. sea otters). If the fur becomes matted with oil, they rapidly lose body heat and die from hypothermia. At sea, whales, dolphins and seals are at less risk because they have a layer of insulating blubber under the skin. However, there have been oil-related mortalities of young seals at breeding colonies.

Recovery

It is unrealistic to define recovery as a return to prespill conditions. This is partly because quantitative information on prespill conditions is only rarely available and, more importantly, because marine ecosystems are in a constant state of flux due to natural causes. These fluctuations can be as great as those caused by the impact of an oil spill. The following definition takes these problems into account.

Recovery is marked by the re-establishment of a healthy biological community in which the plants and animals characteristic of that community are present and functioning normally. It may not have the same composition or age structure as that which was present before the damage, and will continue to show further change and development. It is impossible to say whether an ecosystem that has recovered from an oil spill is the same as, or different from, that which would have persisted in the absence of the spill.

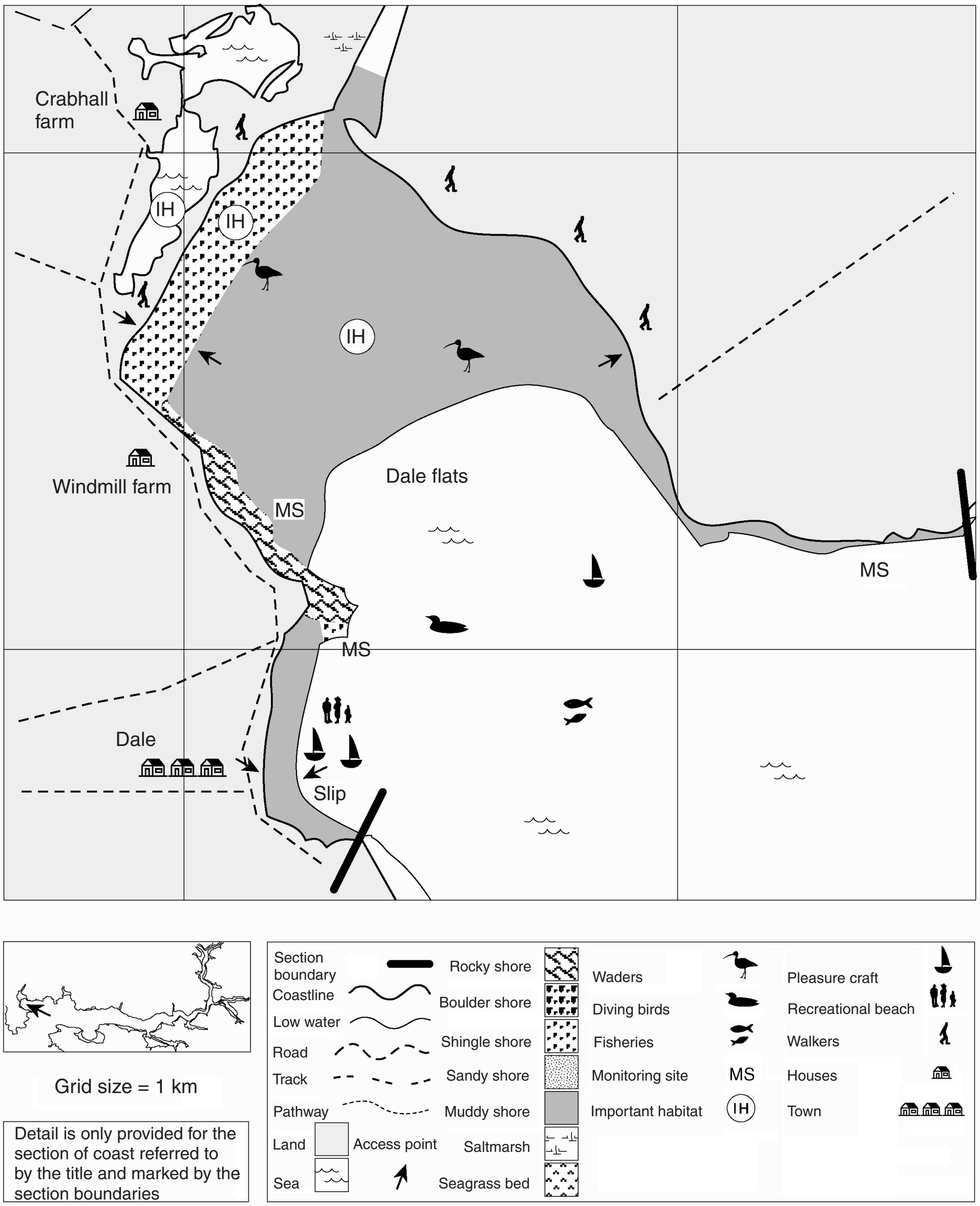

Figure 6 An example of a sensitivity map. This large-scale map is part of an atlas covering the oil port of Milford Haven, Wales. It facilitates response when oil has come near shore or onshore, and the protection or clean-up of specific locations is being planned.

Assessment

Before a Spill

Before a spill it is important to identify what the particular sensitivities are for the area covered by any particular oil spill contingency plan, and to put the information on a sensitivity map which will be available to response teams. An example is shown in **Figure 6**. Maps should include information on the following.

- Shoreline sensitivity. Shorelines may be ranked using the basic principles that sensitivity to oil increases with increasing shelter of the shore from wave action, penetration of oil into the substratum, natural oil retention times on the shore, and biological productivity of shore organisms. Typically, the least sensitive shorelines are exposed rocky headlands, and the most sensitive are marshes and mangrove forests.
- Other ecological resources such as coral reefs, seagrass and kelp beds, and wildlife such as turtles, birds and mammals.
- Socioeconomic resources, for example fishing areas, shellfish beds, fish and crustacean nursery areas, fish traps and aquaculture facilities. Other features include boat facilities such as harbors and slipways, industrial water intakes, recreational resources such as amenity beaches, and sites of cultural or historical significance. Sensitivities are influenced by many factors including ease of protection and clean-up, recovery times, importance for subsistence, economic value and seasonal changes in use.

After a Spill

The response options need to be reviewed and fine-tuned throughout the response period, in the light of information being received about distribution and degree of oiling and resources affected. In extreme cases this process can be lengthy, for example over three years for the shoreline response to the *Exxon Valdez* spill in Prince William Sound, Alaska. In this case information was provided by shoreline clean-up assessment teams who carried out postspill surveys with the following objectives: assessment of the presence, distribution, and amount of surface and subsurface oil, and collection of information needed to make environmentally sound decisions on clean-up techniques. The standardized methods developed have subsequently been used as a model for other spills.

Acknowledgment

The International Petroleum Industry Environmental Conservation Association is gratefully acknowledged for permission to use material from its Report series.

See also

Coral Reefs. Mangroves. Seabirds as Indicators of Ocean Pollution. Seabird Overview. Seamounts and Off-ridge Volcanism.

Further Reading

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OKHOTSK SEA CIRCULATION

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Introduction

The Okhotsk Sea (**Figure 1**) is one of the marginal seas of the north-western North Pacific. The circulation in the Okhotsk Sea is mainly counterclockwise. The Okhotsk Sea is the formation region for the intermediate water layer of the North Pacific. Water entering the Okhotsk Sea from the North Pacific is transformed in temperature, salinity, oxygen, and other properties through ice processes, convection, and vigorous mixing before returning to the North Pacific. Relatively saline water from the Japan Sea assists in making Okhotsk Sea waters denser than those of the Bering Sea, which otherwise has similar