IPIECA

International Association of Oil & Gas Producers

Impacts of oil spills on shorelines

Good practice guidelines for incident management and emergency response personnel



IPIECA

The global oil and gas industry association for environmental and social issues

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Preface

This publication is part of the IPIECA-IOGP Good Practice Guide Series which summarizes current views on good practice for a range of oil spill preparedness and response topics. The series aims to help align industry practices and activities, inform stakeholders, and serve as a communication tool to promote awareness and education.

The series updates and replaces the well-established IPIECA 'Oil Spill Report Series' published between 1990 and 2008. It covers topics that are broadly applicable both to exploration and production, as well as shipping and transportation activities.

The revisions are being undertaken by the IOGP-IPIECA Oil Spill Response Joint Industry Project (JIP). The JIP was established in 2011 to implement learning opportunities in respect of oil spill preparedness and response following the April 2010 well control incident in the Gulf of Mexico.

Note on good practice

'Good practice' in this context is a statement of internationally-recognized guidelines, practices and procedures that will enable the oil and gas industry to deliver acceptable health, safety and environmental performance.

Good practice for a particular subject will change over time in the light of advances in technology, practical experience and scientific understanding, as well as changes in the political and social environment.

Contents

Introduction

Shoreline ecosystems and services

Shoreline ecosystems encompass a large variety of habitats, ranging from the steep rock, mobile pebbles and clean sand of open coasts to the soft mud, brackish marsh and dense mangroves within estuaries and other sheltered inlets. They are colonized by many species of plants and animals, and provide food and shelter to many others. They also provide various benefits to neighbouring ecosystems and to the wider environment. The many benefits that humans receive from these habitats and communities are referred to as ecosystem services.

Shoreline habitats are often areas of high biological productivity (i.e. the amount of organic material produced by plants and animals) and this can be so large that there is a considerable net export to neighbouring marine ecosystems. This is mostly in the form of decaying plant material and eggs, spores and larvae.

In addition to the large variety of plants, algae (seaweeds) and invertebrates that are permanent dwellers on shorelines, many vertebrates also rely on shoreline resources. Many birds, fish, mammals and reptiles use shorelines for foraging on the large variety of organisms that are present. Some species, like turtles and various fish, lay their eggs in shoreline habitats. Others, like seals, walruses and many birds, haul out and rest there. Some shorelines, particularly mangroves and saltmarshes, are important as nursery areas for many fish, including commercial species, providing shelter, protection and food to the juvenile stages as they grow before they join the adult stocks.

Shorelines provide natural protection for coastlines from the effects of the sea. Mangroves and saltmarshes, in particular, form a dynamic buffer between land and sea, that provides flood defence and erosion protection. Other important services to humans include water treatment (removal of contaminants, nutrients and sediments that run off the land), and provision for fisheries (particularly shellfish), aquaculture (particularly shellfish and seaweed), recreation, culture and aesthetics.

Oil spills from shipping, offshore exploration and production, pipelines or land-based facilities can be a threat to shorelines. As most oil floats and oil slicks are moved by wind and currents, spilled oil often has the potential to reach the shore. Contamination of shorelines by oil can have a consequent impact on the various functions and services provided by those habitats, and can also impact the populations of species associated with the affected shorelines.

Purpose of this document

This document provides an overview of how oil spills can impact shoreline resources and functions, and how quickly those resources and functions can recover. It covers habitats and species characteristic of the intertidal zone (i.e. the area that is above water at low tide and under water at high tide) of marine and estuarine shores. It is based on documented scientific evidence, includes references to specific studies, and is aimed at the general response community consisting of operators, governments, businesses and the public.

The first section, entitled *Oil on shorelines: fate, persistence and natural removal*, describes the fate of oil on different shorelines and the characteristics that are relevant to impacts and recovery. Emphasis is placed on those characteristics and processes that affect oil persistence, as they are most likely to influence long-term effects.

The section on *Ecological impacts of oil on shorelines* provides a general description of the susceptibility of different shoreline organisms to oil, and habitat-specific descriptions of typical impacts, resilience, expected recovery rates and the main factors that determine them.

The third section, entitled *Shoreline treatment and restoration,* considers current good practice for shoreline clean-up and how it is designed to maximize net environmental benefit. Descriptions of the potential advantages and disadvantages of the main treatment options are provided, together with examples of past restoration projects.

The fourth section, on *Assessment and monitoring of oiled shorelines*, summarizes some of the fundamental approaches and requirements of impact assessment, with a focus on the Shoreline Clean-up Assessment Technique (SCAT).

Finally, the *References and further reading* section provides a list of references and relevant publications.

The IPIECA-IOGP Good Practice Guide (GPG) series includes a number of other titles, in particular the GPG entitled *Impacts of oil spills on marine ecology* (IPIECA-IOGP, 2015a) which provides a wider discussion on the topic of marine oil spill impacts. Other titles with direct relevance cover subjects including net environmental benefit analysis (IPIECA-IOGP, 2015b), sensitivity mapping for oil spill response (IPIECA/IMO/IOGP, 2012) and oiled shoreline assessment (SCAT) surveys (IPIECA-IOGP, 2014). For a discussion on the impacts of oil spills on inland/freshwater shorelines of lakes and rivers see the GPG on inland response (IPIECA-IOGP, 2015c).

Oil on shorelines: fate, persistence and natural removal

Crude oil and most oil products are complex mixtures of hydrocarbons (for the purposes of this document the term hydrocarbon is used generically to include all of these organic compounds) that vary in their molecular weight, and in their physical and chemical characteristics. If spilled into the marine environment the oil is exposed to a number of processes that quickly and progressively change its character and redistribute much of it into other parts of the environment. The characteristics of different oils and the oil fate processes that take place in the sea are described in the Good Practice Guide entitled *Impacts of oil spills on marine ecology* (IPIECA-IOGP, 2015a). Over time, any remaining oil on the sea surface typically becomes more viscous and less acutely toxic, a process known as weathering. In some circumstances the oil may remain at sea and never reach the shore. In very cold climates where ice forms along the coast during the winter months it can form a barrier that prevents shoreline oiling. However, in other circumstances it can reach the shore, and it may do so in a variety of different forms. These can include: thin sheens; fresh light oils, which tend to have a greater acute toxic effect; heavily weathered oils and emulsions (often called mousse), which tend to have more of a smothering effect; and small lumps of weathered oil referred to as tar balls. In addition, shoreline organisms may also be exposed to dissolved or dispersed hydrocarbons in the water. The process of dispersion is further enhanced by waves breaking on the shorelines.

If oil reaches a shoreline its fate is dependent on a range of additional factors including the shore's topography and composition and exposure of the oil to wave and tidal energy, as well as the characteristics of the oil when it arrives. Figure 1 illustrates some of these factors. An extreme example is that of a vertical rock wall on a wave-exposed coast, which is likely to remain unoiled if an oil slick is held back by the action of the reflected waves. However, most mangroves and saltmarshes are so sheltered from waves and tidal currents that once oil is deposited it can persist for many years.

Oiled shore and clean-up (diggers and water bowsers just visible) on the upper shore of Angle Bay in Milford Haven, Wales, illustrating patchy distribution of oil from the 1996 Sea Empress *oil spill.*

Mats of oil mixed with sand, lying on the lower shore and shallow subtidal of Grand Isle, Louisiana, during the Macondo well incident in the Gulf of Mexico, 2010.

In some conditions, breaking waves on beaches can mix floating oil with suspended sediment in the surf zone. The oily sediment is then heavier than water and sinks, which can result in the formation of tar balls and tar mats in the shallow subtidal zone just off the beach. This was a feature of shoreline oiling in some areas following the Macondo incident that took place in 2010 in the Gulf of Mexico.

The complex patterns of water movement close to coasts tend to concentrate oil in certain areas. Some shores are well known to act as natural collection sites for litter and detached algae, and oil is carried there in a similar way. The distribution of different substrata, as well as natural and man-made features such as headlands, reefs, rock ridges, gravel banks, streams, sea ice, breakwaters and seawalls, at a range of scales, also affect where oil is concentrated on a shore. Oiling is usually patchy, even on relatively uniform coasts; the majority of the oil is typically concentrated on a small proportion of the total shoreline affected, while most of the shoreline is exposed to no more than light oiling or sheen.

Oil tends not to remain on permanently wet surfaces, including most algae, but is likely to stick firmly if the substrate dries out after the tide has receded. The middle and lower intertidal zones are exposed to floating oil and dissolved hydrocarbons during the tidal cycles, but there is less chance of stranded oil remaining on the lower shore areas. However, along the high tide mark and within the upper intertidal zone, sediments are often less saturated with water and the oil becomes stickier on warm, rough surfaces, hence there is less potential for remobilization of deposited oil by subsequent wave and tidal action. Ice-covered shores provide some protection from oil and may limit its persistence, but oil can also be trapped on shores by ice.

Some oils can penetrate into shoreline sediments, depending on factors such as porosity (related to sediment type and size), the depth of the water table, the viscosity of the oil and the presence of animal burrows or pores left by decayed roots. Penetration of oil is unlikely in most tidal flats, due to the fine particle sizes and because they are often water saturated. However, a low viscosity oil might penetrate to depths of around a metre on a well-drained sand or gravel shoreline or into crab burrows. Pebble/cobble beaches have the highest potential for penetration and are more common at higher latitudes, particularly where they were supplied by glacial debris and there is less fine material to fill the gaps. Oil that has penetrated these coarse sediments may then form a surface or subsurface layer that can be highly persistent. This was demonstrated by the Baffin Island Oil Spill (BIOS) Project (1980–1983) in Canada's eastern Arctic. The BIOS Project was one of the largest field experiments carried out to observe the fate and effects of spilled oil, and also showed that, in cold climates where oil viscosity is relatively high and there are few large animal burrows, penetration into fine sediments is unlikely.

Stranded oil can become buried through various processes, especially during storms. It can also be trapped in marshes

Peter Taylor

Viscous oil from the Worthy *oil spill in 1989 did not penetrate the sandy sediment in Southampton Water, England.*

Oil from the 1991 Gulf War spill contaminating burrows of crabs in upper shore saltmarsh areas of Saudi Arabia, allowing oil to penetrate deep into these fine sediments.

A layer of oil buried under sand near Manifah, Saudi Arabia, during the 1991 Gulf War oil spill. This photograph was taken 11 years after the spill (pencil indicates scale).

and be buried by incoming sediment. Burial of oil was a notable feature of many sandy shores during the 1991 Gulf War oil spill and the 2002 *Prestige* incident, with layers of oil covered by a metre of sand in some locations. It is also possible for buried oil deposits to become re-exposed by the opposing processes of erosion.

Once oil has arrived at the shore, the waves and tides that carried it onto the shore gradually remove it again, at a rate that is dependent on many factors. Exposure of the oil to waves, tidal currents, weather and climate, and the characteristics of the shore are all significant factors. A patch of oil exposed to heavy wave action is unlikely to remain on the shore for long, particularly if mobile sediments provide additional scouring action. On Arctic shores ice scour can also remove oil residues. However, where oil becomes trapped in a sheltered inlet, such as a marsh or mangrove, it could take many years for the limited water movement to remove the trapped oil. Even on relatively exposed shores, small scale topographic features and stable rocks provide localized shelter where oil residues can persist. Weather conditions such as rainwater or storm water run-off, heat and sunlight add to the weathering processes of oil lying on a shoreline, while the presence of clay particles in the water can help to remove oil from shore substrata by a process of flocculation.

Biodegradation of the oil to carbon dioxide and water is the ultimate fate of most oil from spills, but the rate of degradation depends on a number of factors, particularly the type and molecular weight of the hydrocarbons and the surface area available for microbes to attack the oil. Oil that has been remobilized from the shore, either as small droplets or fragments, or attached to clay particles, is therefore available for relatively rapid biodegradation by bacteria in the water column. Larger fragments may settle out on the seabed.

In this muddy sand, the natural anoxic 'black layer' can be seen beneath the 1–2 cm deep oxygenated top layer. Anoxic muddy sediments are naturally black due to the formation of iron sulphides where there is insufficient oxygen for formation of iron oxides, and are sometimes mistaken for oil. They may also smell of hydrogen sulphide (the 'rotten egg' smell), which can also be mistaken for an oily smell.

If oil penetrates sediments or becomes buried below the surface it is likely to be more persistent because it is less exposed to water movement that could otherwise remove it, and because reduced oxygen and nutrient availability slows microbial degradation. In muddy sediments with poor drainage, oxygen permeability can be so low that anoxic conditions develop. The bacteria that live in anoxic conditions can degrade hydrocarbons, but do so more slowly than those in oxygenated sediments. Degradation of buried oil deposits can be so slow, depending on local conditions, that they retain recognizable characteristics of their original chemical composition for many years. The same oil buried in a well-oxygenated sediment will be more rapidly degraded, but may still remain as a persistent subsurface layer in some shoreline environments. In time, biodegradation reduces the toxicity in the sediment and allows recolonization by an increasing number of animals and plants.

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Residues of oil from the 1974 Metula *spill in Tierra del Fuego, Chile, still remain in areas of saltmarsh. In warmer climates it would have been more rapidly broken up and degraded by the more active colonization and growth of plants and microorganisms.*

Persistence is also affected by water temperature and climate, as oil is more viscous in cold environments and biologically mediated processes may be slower. Biodegradation of oil by bacteria can occur rapidly in water and sediments in any climate, but the reworking of contaminated sediments by plants and animals is slower in polar regions, particularly over winter periods. In places where shoreline sediments can freeze, penetration of oil may be limited.

As oil weathers it becomes more viscous and less acutely toxic, sometimes remaining as a tarry residue on the upper shore. Such residues typically contain a large proportion of high molecular weight hydrocarbons that biodegrade only slowly. Persistence of oil residues is also a function of their thickness, as weathering and bacterial activity only occur at the surface of the oil. In situations where oil becomes mixed with loose gravel at the top of a shore it can form an 'asphalt pavement'. Such residues and pavements can remain for years, grossly altering the habitat and

Box 1 *Terminology*

Vulnerability and **sensitivity** to oil: vulnerability describes the likelihood that a resource will be exposed to oil. Sensitivity assumes that the resource is exposed to the oil, and describes the relative effect of that exposure. Thus, a deep water coral may be sensitive but not vulnerable to a surface oil spill, while a rocky shore seaweed may be vulnerable but not sensitive.

Toxicity is the inherent potential or capacity of a material to have adverse effects on living organisms; aquatic toxicity is the potential of a chemical to have toxic effects on aquatic organisms.

Exposure is the combination of **duration** of exposure to the chemical and **concentration** of the chemical.

Exposure route is the way the organism is exposed to the substance, including ingestion (directly or in food), absorption through the gills or contact with the skin.

The **magnitude** of a toxic effect depends on the sensitivity of an organism to the chemicals, but is also a function of both the concentration and duration of exposure to the chemical.

Acute and **chronic** toxicity: acute toxicity involves harmful effects in an organism through a single or short-term exposure. Chronic toxicity is the ability of a substance or mixture of substances to have harmful effects over an extended period, usually upon repeated or continuous exposure, sometimes lasting for the entire life of the exposed organism.

Bioavailability is the extent to which a chemical is available for uptake into an organism and determines that chemical's ability to express its toxicity and its rate of biodegradation.

Residual oil from the 1989 Exxon Valdez *spill persists in some boulder shores in Prince William Sound, Alaska, where heavy oiling soaked into layers of porous sediment protected from weathering processes by overlying rock and pebble structure.*

blocking colonization. In Milford Haven, Wales, tar residues resulting from the bombing of oil storage tanks in August 1940, during the Second World War, are still present on a nearby rocky shore. Once the surfaces of these tarry patches have hardened by weathering, any remaining toxicity is effectively trapped inside. Gradual leaching of hydrocarbons from oil residues may result in a prolonged low-level (chronic) exposure to nearby marine organisms. However, the more persistent the oil is, the slower such leaching will occur and, as a result, the concentrations of hydrocarbons in the surrounding water may be so low that they have no significant toxic effect. This is considered to be a similar situation to that in some intertidal areas of Prince William Sound, Alaska, where relatively small amounts of oil residue from the 1989 *Exxon Valdez* spill persist under boulders. Evidence from biomarker studies of continued exposure of otters and some birds to hydrocarbons, up to nine years after the spill was linked by some researchers to the persistent oil residues, but other researchers concluded that these residues did not lead to any significant ecological effect. Further discussion on acute and chronic toxicity is given in the IPIECA-IOGP Good Practice Guide on the impacts of oil spills on marine ecology (IPIECA-IOGP, 2015a).


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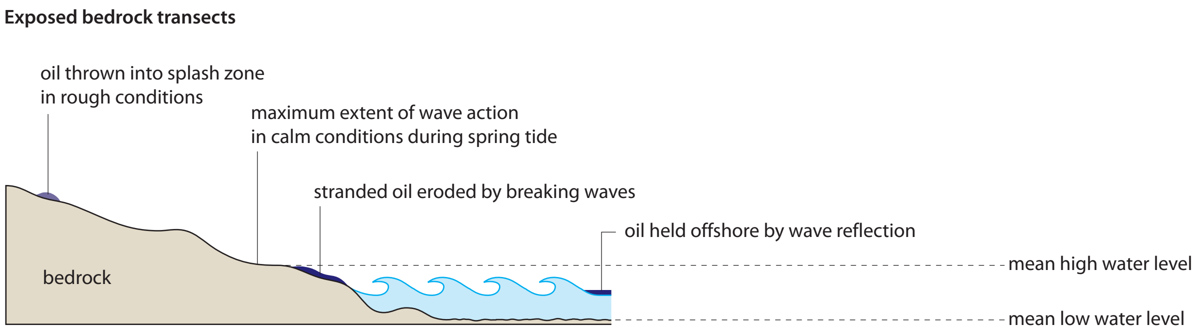
Recovery of contaminated habitats typically occurs by a process of gradual succession. As toxicity reduces due to biodegradation and weathering, an increasing number of animals and plants will recolonize. Some species can withstand high concentrations of oil and long periods of exposure to the oil without suffering toxic effects; these tend to be the first species to opportunistically recolonize the habitat. These opportunists may then help to break up the oil and enhance degradation, paving the way for other, more sensitive species to colonize.

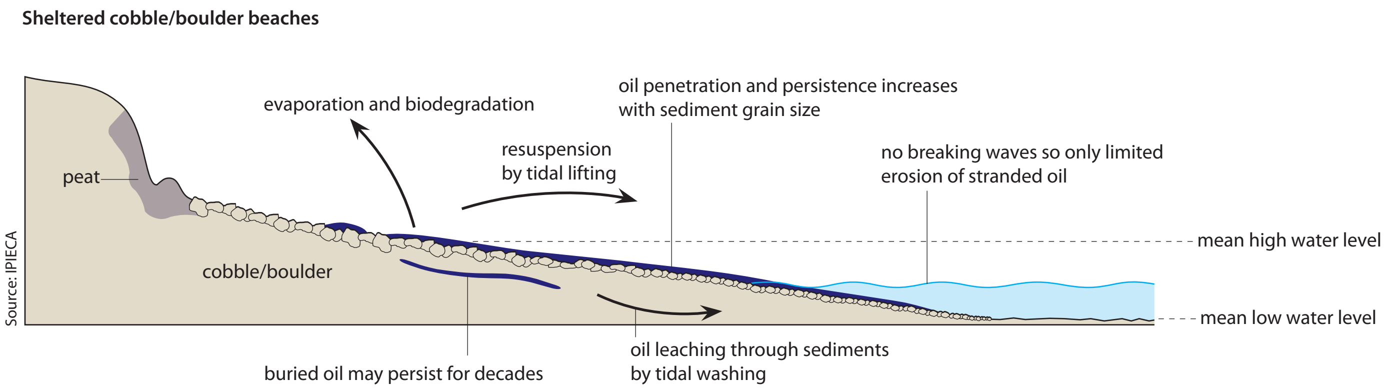
Tar covering beach rock on the Egyptian coast of the Red Sea. The few species that are adapted to live on these shores need shady refuges out of the sun. Tar residues can smother these hollows and reduce habitat availability.

Current interpretations of ecological recovery focus upon the functions provided by a contaminated habitat rather than the contamination itself, but where long-term impacts of oil spills occur, they are most often due to persistent contamination. Understanding the persistence of oil in different situations is therefore the key to assessment of the recovery time. However, the scale and form of the persistent contamination is important when considering its ecological significance, together with an understanding of natural background levels of hydrocarbons and the context of other natural and anthropogenic stressors. Rapid recovery after oil spills is the norm for most affected areas. Slow recovery is usually limited to small portions of the shoreline where oil is more persistent. A primary objective of oil spill response is to limit the risk of oil reaching shorelines that are predisposed to long-term persistence. The following spills illustrate the importance of oil type and wave exposure on persistence and recovery:

- Heavy fuel oil from the 1970 *Arrow* spill contaminated more than 300 km of the Chedabucto Bay shoreline in Nova Scotia, Canada. Most areas were left to natural clean-up, and a detailed survey in 1992 found residual oil on 13.3 km of shoreline, with heavy oiling restricted to 1.3 km of the most low-energy shores. Studies of the impacted intertidal communities carried out at the time of the spill showed that there were significant mortalities of many species, including softshell clam in Black Duck Cove. Recruitment of this clam was greatly affected by persistent contamination, but improved as the oil weathered and toxicity declined. Six years after the spill, toxic levels of oil still remained in sediments in the Cove, and clam growth rates were significantly reduced. Later surveys, carried out 23 and 27 years after the spill, found that sediments from those sites still contained significant hydrocarbon concentrations but toxicity was much lower, as measured by exposure effects indicators in flatfish and in other toxicity tests.
- Light North Sea crude from the 1996 *Sea Empress* spill oiled around 200 km of Pembrokeshire shoreline in Wales. Clean-up operations removed oil from some shores, and were focused on tourist beaches, but the majority of the shoreline oil was left to natural clean-up. Studies documented significant acute impacts on shore life, but almost insignificant quantities of oil were evident within less than three years, comprising a few small patches of tar and asphalt pavement in very sheltered locations. Almost all known impacts on wildlife and coastal habitats had disappeared within five years.

Figure 1 *Example of the fate of oil on shorelines*





Environmental Sensitivity Index

The Environmental Sensitivity Index (ESI) is a 10-point scale that integrates all of the factors described above, and more, to classify shorelines according to the likely persistence of oil. The higher the ESI number, the greater the potential oil persistence. As persistence of oil is the primary cause of long-term impacts, the scale can be used to assess recovery potential. However, it is designed primarily for categorizing shoreline types on sensitivity maps used during an emergency response, to aid response decisions, prioritization and selection of the most appropriate shoreline treatment techniques. Further information can be found in the IPIECA-IOGP Good Practice Guide on sensitivity mapping for oil spill response (IPIECA/IMO/IOGP, 2012).

Table 1 summarizes the general features of the ESI scale. The scale has been adapted for some regional shorelines, with subcategories specific to those regions, but these are not included here.

Table 1 *General features of the ESI scale*

ESI	Shoreline descriptions
1	a) Exposed rocky shores. Steeply sloping. Oil is typically held offshore by reflecting waves. Any oil deposited is rapidly removed by wave action. Impacts on intertidal communities are typically short term, unless acute exposure of a fresh light oil product causes high mortality. b) Exposed, solid man-made structures. Includes seawalls, piers etc. Similar to above.
2	a) Exposed wave-cut platforms in bedrock. Shelf or platform of variable width and gentle slope. Often backed by a steep scarp, sometimes with sediment at base. Pools and crevices are common, possibly with some loose gravel. Oil will not adhere to the platform, but may accumulate among gravel at the high tide line. Persistence is usually short term. b) Exposed scarps and steep slopes in clay. Generally occur along channels through wetlands where currents cut a steep bank. Oil does not adhere to the clay surface, but possibly at high water mark. Any oil deposited is rapidly removed by water movement.
3	a) Fine- to medium-grained sand beaches. Flat to moderately sloping and hard packed. Wrack may accumulate along the strandline. Oil may cover large areas, but will lift off the lower beach and become concentrated along the upper intertidal zone. Oil may penetrate sand or become buried and there may be a decline in sediment fauna. These beaches are among the easiest to clean. b) Scarps and steep eroded slopes in sand or peat. Occur where sand bluffs are undercut by water. Can have a narrow beach along the base, but their use by fauna is limited. Can have seasonal importance for birds. Stranded oil will concentrate at the high tide line and may penetrate sand. Oil residence time is usually short.
4	Coarse-grained sand beaches. Moderate slope of soft sediment. Sediment fauna is limited. Oil may cover large areas, but will lift off the lower beach and become concentrated along the upper intertidal zone. Oil may penetrate sand or become buried to depths greater than 1 m and there may be a decline in sediment fauna. Sediment is too soft for vehicles. *continued …*

Table 1 General features of the ESI scale (continued)

ESI	Shoreline descriptions
5	Mixed sand and gravel beaches. There may be zones of mobile sand, pebbles or cobbles, and distribution may change. Fauna and flora is generally limited, except on the more stable substrata. Oil may cover the whole beach, but will lift off the lower beach and become concentrated along the upper intertidal zone. Oil may penetrate sediment or become buried. Asphalt pavement may form in sheltered locations.
6	a) Gravel beaches, ranging from pebbles to boulders. Can be steep with wave-built berms. Fauna and flora is generally limited except on the more stable substrata on the lower beach. Stranded oil is likely to penetrate deeply, can be pushed over the high tide line and can be very persistent. Asphalt pavement may form in sheltered locations. Potential for chronic oiling. b) Riprap. Blocks of rock or concrete for shore protection. Oil may penetrate deeply and adhere to rough surfaces. Potential for chronic oiling.
7	Exposed tidal flats. Broad, flat areas of sand with some mixed shell or mud. Usually in tidal inlets. Water-saturated except on higher ridges. Can have dense sediment life and be important for wetland birds. Oil does not adhere to wet sediment, but accumulates at the high tide line and may penetrate at the tops of ridges. There may be a severe decline in sediment fauna.
8	a) Sheltered rocky shores. Variable permeability depending on substrata. Can have high densities of attached fauna and flora. Oil will adhere to rough surfaces along the high tide line, but not on wet lower shore surfaces. Oil will penetrate loosely packed angular rubble with potential for long-term persistence. b) Sheltered, solid man-made structures. Includes seawalls, piers etc. Similar to above.
9	a) Sheltered tidal flats. Soft mud, with some sand and shell. Frequently backed by marshes. Can have dense sediment life and be important for wetland birds. Oil does not adhere to wet sediment, but accumulates at the high tide line and may penetrate burrows. Potential for deposition of contaminated sediments. There may be a severe decline in sediment fauna. b) Sheltered, vegetated low banks. Low banks of channels with grass or tree roots exposed. Oil may cover grasses and trees at high water.
10	a) Saltwater and brackish-water marshes. Temperate and subtropical wetlands dominated by marsh plants. Sediments are organic-rich muds, except on the edge of tidal channels where they may be sandy. Abundant flora and fauna. Oil adheres to emergent vegetation. Heavy oil coating restricted to outer fringe of marsh, but lighter oils may penetrate more deeply. Medium and heavy oils do not penetrate wet sediments, but can pool in depressions. Light oils can penetrate the upper few centimetres. There may be a severe decline in flora and fauna. b) Mangroves. Tropical and subtropical saltwater scrub-shrub wetlands. Variable substrata, but usually muddy. Abundant flora and fauna. Oil adheres to emergent vegetation and tends to concentrate on raised berms or shoreline, where it may penetrate. Potential for chronic oiling. There may be a severe decline in flora and fauna.

Ecological impacts of oil on shorelines

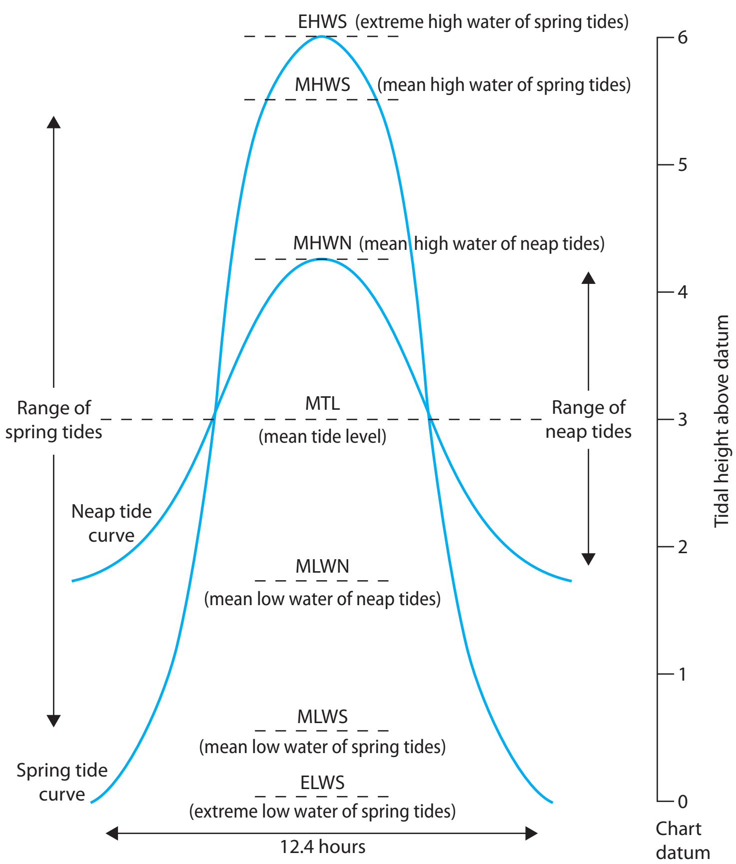
Shoreline life and its susceptibility to oil

Animal and plant species that live on shorelines because of the food, shelter and substrate it provides also experience many environmental stresses. These stresses are related to wave action, sediment movement and tidal changes (see Figure 2) resulting in large daily and seasonal fluctuations in temperature, salinity, desiccation, predation and the availability of food and oxygen. Since the shorelines are so dynamic each species can find its optimal window. The benefits and stresses lead to strong vertical zonation patterns between the top of the shore, where many of the organisms are robust, and the lower shore where there is a tendency for greater biodiversity. The shoreline communities are also structured by other environmental factors relating to their habitat, including substratum type, erosion and deposition, aspect (in relation to the sun) and biogeographic zone. In polar regions the shores are also strongly influenced by ice scour. The effects of oil contamination on species and communities are greatly influenced by all of these physical factors, as well as biological sensitivity which varies from species to species.

The ecology of the shallow subtidal zone is closely associated with its adjacent shoreline and, as described in the previous section, some of the physical processes affecting shoreline oil can result in increased exposure to oil in the shallow subtidal zone. These areas are often characterized by

The cycle of tides is controlled by the gravitational force of the moon and sun, so that the lunar cycle of approximately four weeks goes from spring tides (full moon) to neap tides (half moon, waning) to spring tides (no moon) to neap tides (half moon, waxing) and back to full moon.

Figure 2 *Typical cycle of diurnal tides*



high biodiversity and productivity. Further reference to shallow water habitats and communities are given in the sections below and in the IPIECA-IOGP Good Practice Guide on the impacts of oil spills on marine ecology (IPIECA-IOGP, 2015a).

Coastal lagoons are also closely associated with their adjacent shorelines and are particularly important in some parts of the world, for example in the Arctic. They are exposed to environmental fluctuations that tend to limit their biodiversity, but they can have high productivity and are often characterized by specialized species. Water exchange with the sea is, by definition, restricted, so significant penetration of oil may also be limited. However, oil that does penetrate would be likely to persist and may have ecological impacts.

Most species go through seasonal stages in their behaviour or biology (e.g. migrating, breeding, spawning and moulting), which can greatly affect how vulnerable they are to an oil spill. On shorelines, this is most strongly apparent in the migratory patterns of wetland birds, the nesting behaviour of turtles and the seasonal development and dieback of saltmarsh plants. These and others are discussed further in the subsections below.

Shoreline plants and invertebrates

All intertidal species can be potentially affected directly or indirectly by oil contamination, but some are more vulnerable or sensitive than others. The majority of seaweeds, for example, are naturally protected by a mucous coating that resists oil, and there have been many observations of severely oiled seaweed that has cleaned up and survived apparently unharmed without any assistance from humans. On the other hand, mangroves can be killed by any viscous oil that smothers the breathing pores on their prop roots; mangroves depend on these pores for delivering oxygen to the plant.

David Levell

This photograph shows a rectangular area of rock (centre) that was left uncleaned, surrounded by rock that was pressure washed to remove oil following the 1996 Sea Empress *spill. Pressure washing also removed algae and other shore life that took at least two years to recolonize. Algae that was oiled but not cleaned appeared to be unaffected by the contamination.*

Depending on where and how an organism lives it may be exposed to shoreline oiling in a variety of ways, and the mechanism of effect can also vary. Direct physical oiling of plants and animals on the surface of the shore can smother and interfere with feeding. In addition, prolonged exposure to high concentrations of oil may result in toxicity. If oil does not penetrate into sediments, animals in those habitats may be much less affected. Similarly, exposure to dispersed oil in the water overlying intertidal and shallow subtidal habitats will be greatest for filter feeders, but many sediment burrowing animals will be relatively protected.

Filter feeding mussels covered by water at high tide. Water is taken in by the larger (frilly) inhalant siphon and pushed out of the smaller exhalent siphon. Oil can also be taken in, absorbed by the body and then gradually released.

Mussels, clams and oysters are filter feeding bivalves, that actively filter large volumes of water through their bodies to capture particles of organic matter. Consequently, they can accumulate concentrations of hydrocarbon in their tissue, which they cannot readily metabolize and that can take weeks or months to purge from their systems (this process is called depuration). Bivalves are therefore often used as indicators of hydrocarbon exposure and recovery. The bivalves can survive high concentrations of oil in their tissues, but some toxicological studies have shown that sublethal effects may occur, including reduced growth, reproductive capacity and other tissue effects.

Many marine snails are grazers that are vulnerable and sensitive to acutely toxic oil coating the surfaces they graze upon. Impacts on the populations of these species, and the consequent effects on the abundance of the plants and algae they feed on, have been described following many oil spill incidents.

Small crustaceans, particularly amphipods (a highly diverse group of small shrimp like animals), display acute toxic effects when exposed to fresh oil. Studies of intertidal sediments or algal turf communities that are normally colonized by high densities of amphipods have found that their populations are often depleted if those habitats are exposed to significant concentrations of water soluble or dispersed hydrocarbons over long durations.

Many other invertebrates, including sponges, corals and sea-squirts, are physically attached to rocks, plants or other immobile substrata, so even if they are exposed to hydrocarbons and display toxic effects they will not be washed away. Most of these species prefer habitats that do not dry out at low tide, for example on the lower shore or in wet or shady habitats like pools and overhangs. The majority of these species, even where hydrocarbon concentrations have been relatively high, are likely to survive except where there is localized prolonged exposure or smothering from a persistent oil. Many post-spill studies have shown limited impacts on these sessile invertebrates unless the substrata they live on is disturbed.

As described in the previous section, the slow recovery of a shoreline community is most often due to persistent oil, and recovery of the contaminated habitat typically goes through successional stages. However, recovery may still be slow in situations where oil is not persistent. The rate of recovery is then determined by the speed of ecological processes, including recruitment of new colonists, competition between species and growth. Recolonization of shoreline algae and most invertebrates is by settlement of spores and larvae from the plankton which typically occurs annually or more frequently. The rate of recolonization by this means depends on many biological and environmental factors, but is unlikely to be significantly affected by an oil spill if there are no persistent residues. Other invertebrate species do not have a planktonic larval stage, and their recolonization will be by migration from neighbouring shoreline areas. Again, the rate of recovery depends on many factors but may be slower if populations have been depleted over an extensive area. One of the reasons for slow recovery of some rocky shore communities following the 1967 *Torrey Canyon* spill was due to slow recolonization by a species of limpet (a mollusc) at the edge of its geographic range. Slow growth rate can also result in longer-term impacts, particularly when the affected species provides a key structural role in a community that increases with the size of the individual organisms. The best example is mangroves, which develop large associated communities as they grow, but size is also important in the ecological role of other slow growing organisms. A large bivalve, for example, has a far greater capacity for filtering water, excretion and production of eggs and sperm than any number of juveniles colonizing the same area of seabed. Finally, impacts from clean-up activities can also result in slow recovery, and this is discussed in the next section of this document.

Species-rich lower shore habitat, with kelp holdfast, sponges, sea-squirts, encrusting coralline algae and fish eggs.

Shoreline vertebrates

Shorelines provide an important feeding, breeding and nursery habitat for many species of fish when the tide is in, while many juvenile and some adult fish take refuge in pools or lower shore habitats when the tide is out. Some migratory species, like salmon and eels, can cross intertidal areas as they travel to or from freshwater habitats. Contamination of shoreline habitats by oil has the potential to affect these species, and post-spill studies have described impacts on shoreline fish populations. Pacific herring lay their eggs attached to kelp plants on the lower shore and shallow subtidal zone, where they are vulnerable to dispersed and dissolved oil in water. Oil from the 2007 *Cosco Busan* spill was shown to have toxic effects on herring embryos and was linked to high rates of embryo mortality in San Francisco Bay. Larval and juvenile stages of fish are sensitive to hydrocarbons, but the reproductive strategies of most species allow for the huge losses of young that typically occur through predation and other causes of mortality. A very small proportion need to survive to maintain adult populations.

Herring eggs on lower shore.

Dunlin feeding at low tide.

Shorelines, particularly tidal flats and the muddy banks of sheltered inlets, also provide important feeding, roosting and nesting grounds for many species of waders, wildfowl and other bird species. Many species are migratory and may aggregate in large numbers just before and during their seasonal movements. They are most vulnerable to oil spills at those times. However, their vulnerability to oil spills is largely defined by the amount of time that they sit on the surface of the sea, and as the majority of migratory species do not spend that much time on the surface their potential for oiling is much less than that of many other coastal birds. Mortality rates, therefore, are typically low, relative to the regional populations at the time of the spill. Wildfowl that inhabit estuaries and sheltered inlets are more vulnerable because they do sit on the water, though most prefer fresh water. It has been suggested that impacts on food availability may lead to indirect effects on shorebird populations for some species after some spills. In a worst-case scenario this could affect the energy requirements of a wader population. Disturbance from extensive oil spill clean-up activities also has some potential to affect shorebird feeding behaviour and thereby impact their ability to feed efficiently. They will be particularly vulnerable just after long migration flights when their energy reserves are low. Clean-up activity could also disturb the nesting activity of some species, including terns and gulls, which nest on sand spits, shingle ridges and other habitats just above high water near sand beaches.

Southern fur seal hauled out on the shore.

Seals, sea lions and walruses (collectively called pinnipeds) spend varying amounts of time hauled out on the shore, depending on the species, sex, age and time of year. The larger seasonal aggregations tend to form at well-established haul-outs, where they rest after feeding, breeding and moulting. While their bodies are relatively insensitive to oil toxicity, the mucous membranes of their eyes and noses can become inflamed, and pinnipeds will be most vulnerable when they are on or close to their haul-out. Most species also give birth on the shore and in some species the young of the year, which may be vulnerable to smothering by oiling, may remain onshore for many days. Corpses of small numbers of seals, particularly pups, have been reported following several spills, but significant effects on populations have not been identified.

In some parts of the world, female turtles nest above the high tide line of sand beaches, returning to the same site at the same time each year. Their eggs and the newly hatched juveniles would be vulnerable to oil if it arrived there during their nesting season. The nests are buried so the eggs are generally protected, but the hatchlings are more vulnerable as they cross the beach together. These juveniles are more sensitive to oil toxicity than the adults. There have been reports of juvenile turtle deaths following some oil spills. Local population levels may be affected if there were severe impacts on a turtle nesting site in the nesting season, but no such effect has been reported. This is discussed further in the IPIECA-IOGP Good Practice Guide on the impacts of oil spills on marine ecology (IPIECA-IOGP, 2015a)

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Turtle nesting above the high tide line of a sandy shore.

Rocky shores

Rocky shores encompass a wide variety of habitats. They are commonly classified according to wave exposure and tidal zone, but other factors are also important to their ecology and to the potential impacts of an oil spill. Invertebrates and plants living on the open surfaces of rocks are unprotected from the weather and the energy of the sea; but rocky shores are typically rugged on a range of scales, with variable slopes, overhangs, fissures, crevices, caves, pools, surfaces underneath boulders and varying surface textures. Much of the species richness of rocky shores is associated with those features, because they provide a wide variety of habitats and microhabitats with varying degrees of shelter from the sun and from the energy of the sea.

Wave exposure and the strength of water movement are key factors because many plants and animals are not adapted to cope with strong waves and currents that can pull them off the rocks. The persistence of oil is also largely governed by the same forces. Thus, rock surfaces that are exposed to strong wave action are typically dominated by barnacles and limpets that are firmly attached and small mobile snails that can shelter in small crevices. If spilled oil strands on those surfaces it may result in mortality of the affected animals; however, the oil is unlikely to persist and natural recovery processes can begin as soon as concentrations of oil have dropped to levels that do not inhibit re-colonization. Rocky shores in the Arctic are subject to scour from ice, which similarly limits diversity and would also limit the persistence of oil and the potential for impacts. Algae and many other invertebrates are better adapted to rocky shore surfaces that are more sheltered from wave action. Wave sheltered rocky shores, in estuaries and other marine inlets, are therefore typically dominated by a variety of brown, green and red macro-algae, with various invertebrates living on and under the

Steep rocky shore, showing zonation and microhabitats.

algae. Oil deposited in these habitats may not be washed off so quickly and recovery from any impacts may take longer. Man-made structures, including jetty pilings, seawalls and other shoreline protection, are colonized by similar communities and have similar features that increase or decrease the potential for persistence of oil.

The ESI scale includes four categories and two subcategories of rocky shores and man-made hard substratum shores (ESI 1, 2, 6 and 8—see Table 1 on pages 12 and 13) that summarize the likely fate and persistence of stranded oil on these shoreline types. They incorporate, to a certain extent, the influence of slope, pools and other features, but the heterogeneity of rocky shore habitats often makes predictions of impacts and persistence difficult. Most wave exposed shores will have features that are sheltered and where oil may persist, while many sheltered shores have open vertical surfaces where oil is likely to wash off quickly.

Limpets, littorinid snails and other molluscs that graze on algae are one of the groups of rocky shore invertebrates that appear to be most sensitive to acute toxic effects of oil. Mortality of limpets in particular has been widely reported following spills. Limpets play an important ecological role in many rocky shore habitats worldwide and are widely used as the focus of rocky shore monitoring programmes near oil facilities. Studies have shown that even small amounts of fresh oil on a limpet's foot will narcotize it so that it falls off the rock, where it is then unlikely to survive. This effect was well demonstrated during the 1996 *Sea Empress* oil spill in Wales, where there was high mortality of limpets (more than 50% overall and 100% on some surfaces) on the heavily oiled shores close to the source of the spill. However, when large amounts of weathered oil from the same spill reached rocky shores further away, after eight days at sea, oiled limpets on those shores were much less affected due to the greatly reduced toxicity of the oil.

At wave-exposed sites where limpet populations were severely impacted by the *Sea Empress* spill, the last vestiges of oil were removed by the winter storms and recovery of the community went through a series of successional stages similar to those observed following other spills. Without the normal grazing pressure from limpets, green algae flourished rapidly and covered the rock with a dense carpet. Brown fucoid algae, not normally found on wave exposed shores, colonized the shore, became dominant after a year and remained for nearly three years before they were removed by wave action as they grew larger. Meanwhile, juvenile limpets settled from planktonic larvae in the first winter and grew rapidly on the abundant algae. Their population densities had returned to high levels after two years and the age structure had returned to pre-spill conditions within five years.

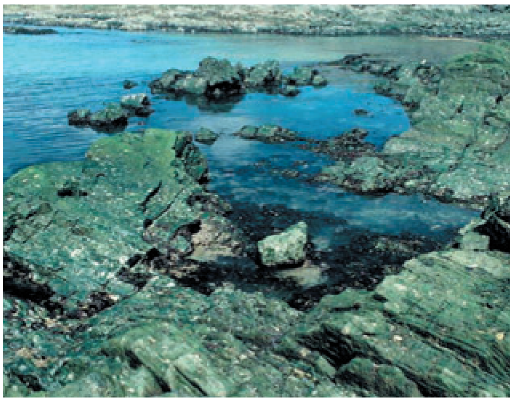
Amphipods, as discussed earlier in this section, are another group of species that are known to be sensitive to oil toxicity, and some species commonly occur in dense turfs of rocky shore seaweeds and in the holdfasts of kelp. Some post-spill studies have described almost complete loss of amphipod populations from rocky shore habitats exposed to high concentrations of oil over a short duration. However, once oil concentrations had returned to background levels, recovery of the affected populations occurred in less than two years, and often within a few months.

Where a viscous oil sticks and dries on rough surfaces or collects in pockets, some invertebrates are prone to smothering. Barnacles are filter feeders that are abundant in many rocky shore habitats; they may suffer heavy mortality if oil sticks to them and stops or impairs their ability to

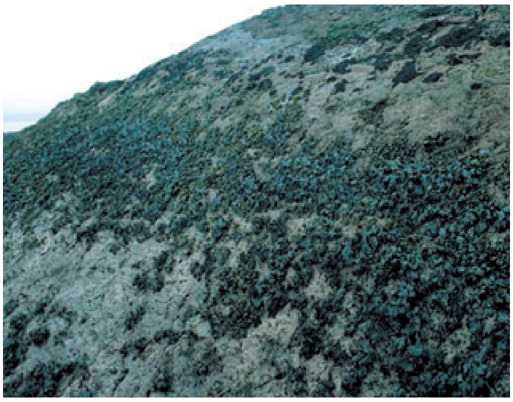
Left: examples of impacts and recovery at West Angle Bay, Milford Haven, Wales, following the 1996 Sea Empress *oil spill.*

(a) After one week: moribund limpets that fell from the rock after being narcotized by fresh oil.

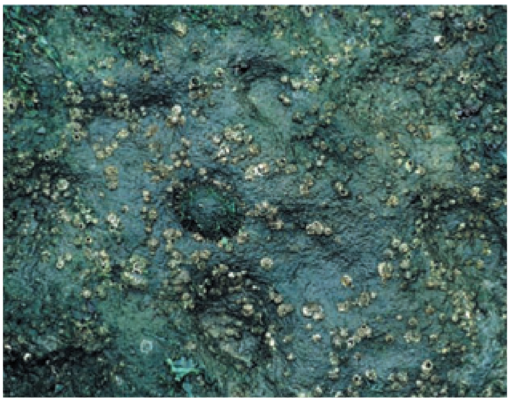
(b) After three months: a solitary remaining limpet where there would normally be high densities, surrounded by a dense flush of green algae resulting from the loss of grazing pressure.



(c) After three months: extensive green flush across the whole of West Angle Bay and the adjacent coast.



(d) After one year: the next stage in colonization—a growth of fucoid algae where settling spores are normally grazed off by limpets.



(e) After one year: surviving barnacles and limpets still covered in green algae.

(f) Five years after the spill: repopulation of the limpet barnacle-dominated community that is characteristic of this site.

feed. Once the dead barnacle cases and remaining oil deposits have been washed away the rock may be recolonized by an annual settlement of barnacle spat and recovery is typically rapid.

While the majority of algae are resistant to the toxicity of hydrocarbons, some of the red algae are relatively sensitive. Coralline algae, in particular, which are often common in lower shore rocky habitats and rock pools, may be bleached and may die due to contact with oil. Lichens, on upper shore rocks above the high tide level, may be vulnerable to oil that splashes upwards during rough weather. These slow-growing plants, each a specific symbiotic composite of an algae and a fungus, can be sensitive to both physical smothering and high concentrations of dissolved oil. Mortality and slow recovery of lichen assemblages have been described following a number of spills, including the 1999 *Erika* spill in Brittany, France.

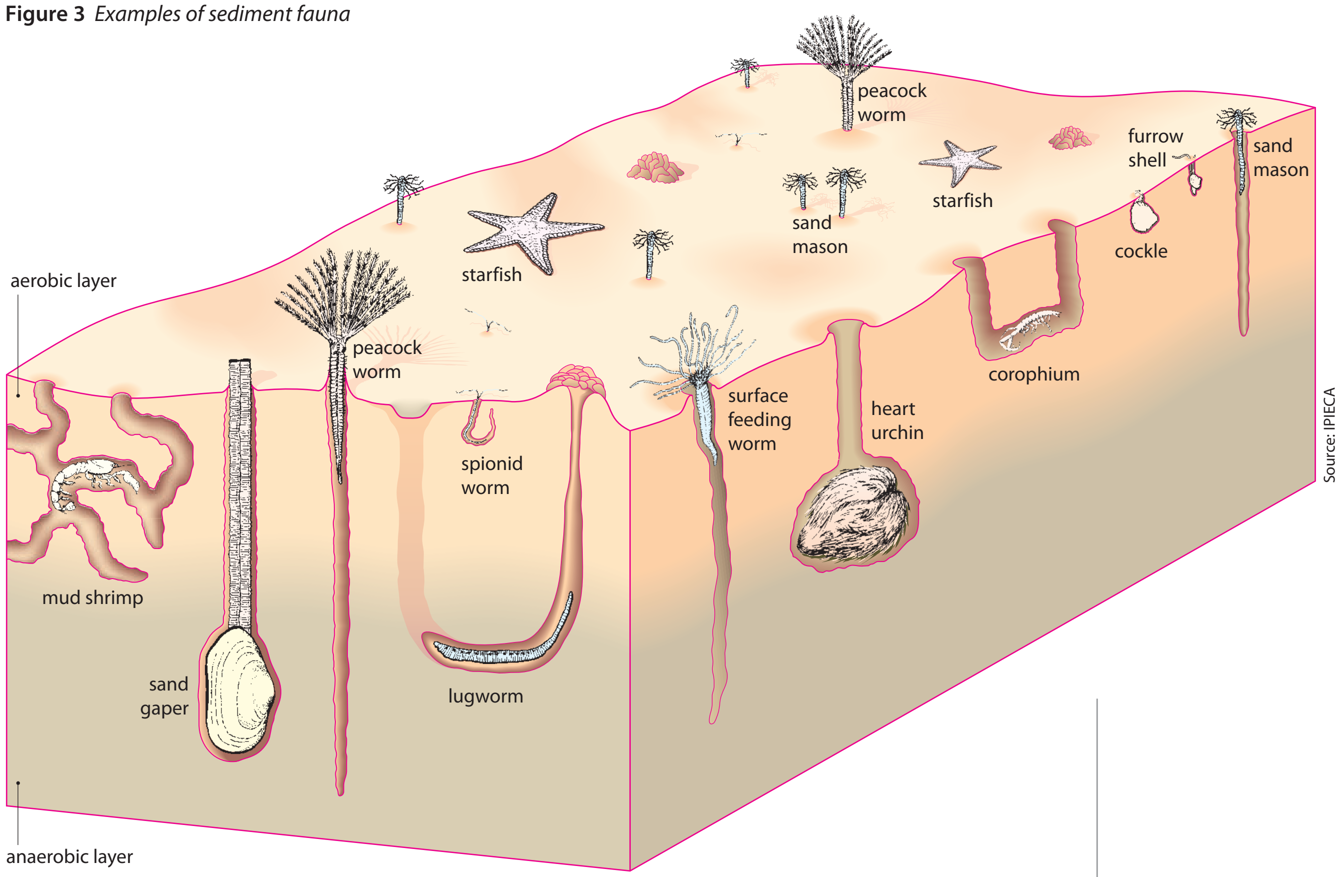
Comparative studies of rocky shore seaweed communities up to two years before, and less than one year after, the 2002 *Prestige* oil spill on the Galician coast of Spain found no discernible changes, even at sites that were heavily oiled.

Locations on rocky shores where a viscous oil can potentially persist include upper shore fissures and hollows protected by rocky ridges, depressions in rock platforms of wave-sheltered shores and in the interstices between or under boulders and rubble. As described in the previous section, these residues typically weather to tar and have very little bioavailability, but they can inhibit colonization of their surfaces. In severely oiled situations the tar can smother shore habitats and reduce habitat complexity. This was evident in Curaçao following the 1986 *Vivita* spill, where substantial tar cover cemented rubble shores and reduced the shaded micro-habitats of snails and other molluscs to such a degree that species richness was still reduced by 35% after seven years.

Sedimentary shores

Intertidal sediments can range from mobile cobble ridges to soft sand beaches, firm clay flats, and complex mixtures of fine and coarse mineral particles. The composition of sedimentary shores typically includes at least some organic debris, and they can display considerable variability in porosity, softness, oxygen penetration, water content and many other physical and chemical characteristics that influence marine ecology. Much of the life in sedimentary shores is hidden below the surface (see Figure 3 on page 23), but some can have a diversity and productivity to rival any above-ground community. Depending on the sediment character and other environmental factors the communities of animals living within the sediment may include high densities of worms, crabs, amphipods and other crustaceans, clams, anemones, sea cucumbers and sea urchins. The size of the organisms can range from microscopic to some long-lived species of clams that can reach weights of more than 1 kg. One basic division used by sediment biologists is between large animals (>0.5 mm, known as macrofauna) that burrow into sediment and small animals (known as meiofauna) that live in interstitial spaces between the sediment particles. Seagrasses form dense beds on some sandy shores and a variety of algae, particularly diatoms and blue-green algae, can create a green film or mat on sheltered tidal flats.

Figure 3 *Examples of sediment fauna*



The ESI scale includes six categories of sedimentary shore (ESI 3, 4, 5, 6, 7 and 9—see Table 1 on pages 12 and 13) because of the large range in sediment shore characteristics and the effect they have on the likely fate and persistence of stranded oil. The ecology of sediment shores and the impacts that oil can have upon them vary considerably, the main factors being wave exposure, sediment composition, mobility and drainage characteristics, organic material input, water salinity and climate. Many of these factors are closely related.

The mobility of the sediment greatly affects the communities of animals and plants that live within them, and relatively few species are adapted to cope with the instability of many sands and gravels exposed to strong waves and currents. The action of sea ice can also result in harsh conditions, and many Arctic shores are very sparsely colonized. Biomass, productivity and species richness of sedimentary shore communities tend to increase as stability increases. Further, relatively few aquatic species are adapted to cope with the stresses of living in upper shore areas unless the sediment is so muddy and water saturated that they are protected from drying out. Thus, the quantity and variety of life in free-draining sediments tends to decrease as one moves higher up the shore.

Arctic shores are harsh environments that are generally sparsely colonized.

An important exception to the above generalization is where detached seaweed and other organic detritus is deposited along the high tide line. This strandline material is to some extent ephemeral and the quantity varies seasonally; nevertheless, it provides important temporary cover and a valuable supply of nutrients to the beach ecosystems, hence it is rapidly colonized by a variety of specialized animals, including amphipods (sand hoppers), insects, spiders and beetles. These animals are opportunistic and their populations fluctuate greatly, but they play an important role in the decomposition of the strandline material. They are also an important prey component for some birds. As any oil that lands on a beach also tends to concentrate in the same area, these strandline communities are particularly vulnerable, but recovery is typically rapid due to their natural facility for rapid recolonization.

The communities of mobile coarse-grained sand and gravel shores (ESI 4, 5 and 6a) typically comprise sparse populations of opportunistic animals that are small (meiofauna) and mobile with short lifespans. If oil penetrates into the sediment or becomes buried, these communities may be severely impacted by acute hydrocarbon toxicity. However, recovery from the oil or from clean-up activity is typically rapid except where persistent oil forms a chronic source of contamination.

The communities of more stable sedimentary shores, particularly those comprising fine sands and muddy sediments (ESI 3a, 7 and 9a) vary greatly in their composition of species, lifestyles, sizes and abundance from one shore to another. They can also be very patchy, which is not as obvious as on rocky shores because the animals are beneath the surface. Vulnerability of the animals to any oil that lands on the shore depends to a large extent on their feeding method. Many sediment invertebrates, including most polychaete worms, feed on organic matter incorporated within the sediment and have little contact with the surface. They are relatively protected from oil on the sediment surface, except where oil penetrates the sediment or becomes buried. However, filter feeders, including bivalve clams and amphipods, and other species that irrigate their burrows with a constant flow of oxygenated water (e.g. some burrowing urchins, shrimps and crabs), are particularly vulnerable to acute hydrocarbon toxicity. They may be exposed to it even if the oil does not penetrate the sediment or become buried. Exposure to dispersed hydrocarbons sometimes results in these animals ejecting themselves from the sediment, whereupon they may then be washed higher up the shore and become stranded.

Clams and tarballs stranded on a beach in Pembrokeshire, Wales, during the 1996 Sea Empress *oil spill. Analysis of tissues from the clams confirmed contamination by oil from the spill.*

During the 1996 *Sea Empress* spill large numbers of cockles, clams and heart-urchins were washed up on sand shores around south-west Wales, though there was little significant contamination of the sediment. Many of the clams and urchins originated from just below the low tide level, in the shallow subtidal, where they are normally present in high densities and vulnerable to dispersed oil from offshore and from the shoreline. With no persistent oil present, the recovery was a function of the natural recruitment processes and growth, and most of the species affected had good recolonization potential via planktonic larvae from unaffected populations in the vicinity. Recovery of most species was considered to be complete within two years, but many bivalves are longer-lived and populations of some species had not returned to pre-spill levels at that time.

Like mussels and oysters, intertidal clams will also accumulate concentrations of hydrocarbon in their tissue, which they cannot readily metabolize. Depending on the concentration and toxicity of the hydrocarbons the clams may show no discernible effect. However, studies on the effects of persistent oil contamination of muddy sediments following the 1970 *Arrow* spill showed a significant reduction in growth rates of clams six years later.

Amphipods, as discussed on page 16, are sensitive to oil toxicity, and some intertidal sediments are characterized by high densities of amphipods. Their populations may be depleted if those habitats are exposed, even briefly, to high concentrations of water soluble or dispersed hydrocarbons. However, recovery of the affected populations is typically rapid.

Crabs, including many that live in burrows, are an important component of many intertidal sedimentary shores in tropical and subtropical regions and can dominate some habitats. The burrows can create a pathway for oil to penetrate below the surface, which may kill the crabs and leave persistent residues. Large areas of tidal flats were oiled during the 1991 Gulf War spill and populations of ghost crabs and other burrowing crabs were severely impacted. Recovery was rapid where oil did not persist or was buried to depths that were greater than their burrows, but 20 years after the spill there were still many areas where crab recolonization was inhibited by oil.

The importance of sedimentary shores for wetland birds, turtles and some other vertebrates is discussed on pages 17–19.

Above left: sheltered tidal flat in Dawhat ad-Dafi on the Gulf coast of Saudi Arabia that was impacted by the 1991 Gulf War oil spill. The photograph, from May 2002, shows Don Aurand, who carried out intertidal surveys in 1992, standing next to a hole that he dug as a sampling station 10 years previously. The presence of the hole, after so many years, is testament to the stability of the habitat, due to its extreme shelter from water movement and the lack of biological activity. This explains the slow natural removal of the contamination.

Above right: the crab burrows visible in the photograph were all unoccupied and still contaminated by oil residue. Experiments have since shown that the crabs can live in these contaminated sediments, but that recolonization is very slow.

The spill disrupted the natural processes of this ecosystem to the extent that excessive growth of algal mats blocked channels and reduced water incursion to the upper tidal flats. Remediation trials are ongoing, but have shown that careful scraping out of blocked channels can increase water flow and enhance recolonization by crabs.

Heavy fuel oil from the 2002 *Prestige* spill contaminated wave-exposed sand beaches along the coast of Galicia, Spain, and was buried under variable depths of sand in many locations. Low concentrations of oil persisted seven years after the spill. Impacts on communities of beach fauna, including reduced species richness and abundance, were shown after six months but there were no detectable effects after seven years.

Analysis of sediments from shores affected by the 2007 *Hebei Spirit* spill, Taean, Korea, described the reduction in hydrocarbon concentrations and their toxicity on exposed sand beaches over five years. However, significantly toxic concentrations remained in sediments from sheltered tidal flats.

Saltmarshes

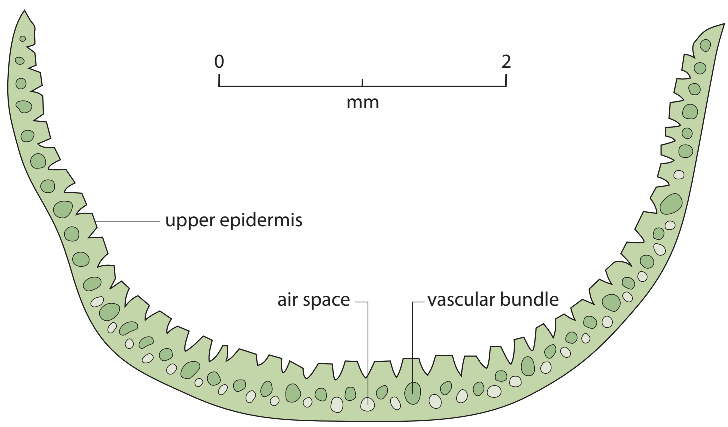
Saltmarshes (also known as halophyte marshes) develop in the upper tidal zones of sheltered muddy shores, where they are exposed to seawater during high tide periods and are therefore vulnerable to floating oil. They can cover large areas and are typically zoned by tidal height; hence the lower areas, just above the level of high water on neap tides, may be dominated by a single plant species, but other plants colonize and have a competitive advantage further up the shore. The number of plant species is typically greatest in the upper marsh areas, which are generally more stable and less often covered by the tide and merge with the terrestrial communities. Marsh plant communities also vary with salinity, region and climate. They often provide an important habitat for birds, including resident breeding species and migratory species during the spring and autumn. Small mammals, amphibians and reptiles can be common in the upper marsh, and small and juvenile fish forage and find shelter in the tidal creeks. Larger mammals frequent marshes in

An extensive saltmarsh.

some regions and farmers may use marshes as grazing land for sheep and other livestock. Small invertebrates, particularly worms, crabs and bivalves, may be present in high densities in the muddy sediment and small snails commonly graze on the stems, leaves and sediment surface. Various algae can also be common.

Saltmarsh leaves, which are often corrugated, provide a large surface area to which oil can stick (see Figure 4). The plant stems and leaves may then be damaged by smothering and chemical toxicity. Fresh, light refined oils tend to have a greater acute toxic effect, while weathered and heavier black oils have more of a smothering effect. If oil settles on the muddy sediment it may penetrate via the burrows of crabs and worms, and pores left by the stems and roots of dead plants, where it may then damage the living roots. However, the extent to which penetration occurs and the effect that it has is highly variable, depending on the acute toxicity and viscosity of the oil and the density and size of burrows and holes. As with most oil spill effects, the more of the plant that is oiled the greater the impact.

Figure 4 *Cross section through a* Spartina *leaf, showing the high surface area of the upper epidermis*



Source: IPIECA

A relatively light oiling of black oil can coat large areas of marsh plants but if the oil does not penetrate into the sediments it is likely that the roots will survive and there is a good chance that the plant will recover. This is typically the case with perennial species which have substantial underground root systems that provide a continuing store of food reserves (carbohydrate and other nutrients) for the plant. In temperate zones, where there is a natural cycle of senescence (dieback) over the winter followed by regrowth in the spring, these perennial saltmarsh plants replenish these stores in the autumn and then draw from them when they start growing again. Thus, a substantial oiling event on a marsh in the winter may have a limited effect on plant survival, but the same spill in late spring, when the underground food reserves are depleted, may have a much greater impact. The resilience of perennial species will also depend on the depth and size of the root system.

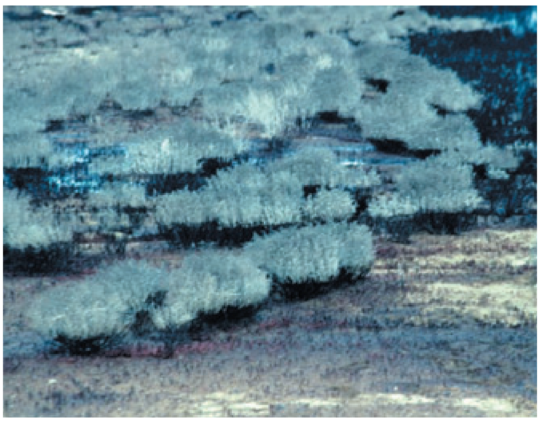
Annual species, which include many of the pioneer species that colonize the lower marsh and other areas of bare ground on the upper shore, are less resilient because they do not have

Michel *et al.*, 2008

Light fuel oil (No. 6 & No. 2 mix) from the pipeline spill at Chalk Point, Maryland in 2000 penetrated to depths of up to 30 cm in brackish marsh sediments, and was concentrated along cavities left by marsh plant roots and rhizomes (visible in photo). Surface sediments in 25% of samples were still toxic to amphipods after seven years. There were also moderate, but statistically significant, ongoing effects of oil on marsh plant biomass (above and below ground). It was predicted by the authors of the study that oil is likely to persist in those marsh sediments for decades.

underground food reserves and rely on annual recruitment by seeds. If seed supply from neighbouring areas is low or the seeds land on a sediment surface that is still contaminated, recovery may be slow. However, many case studies have shown good recruitment of annual species in the year following a spill.

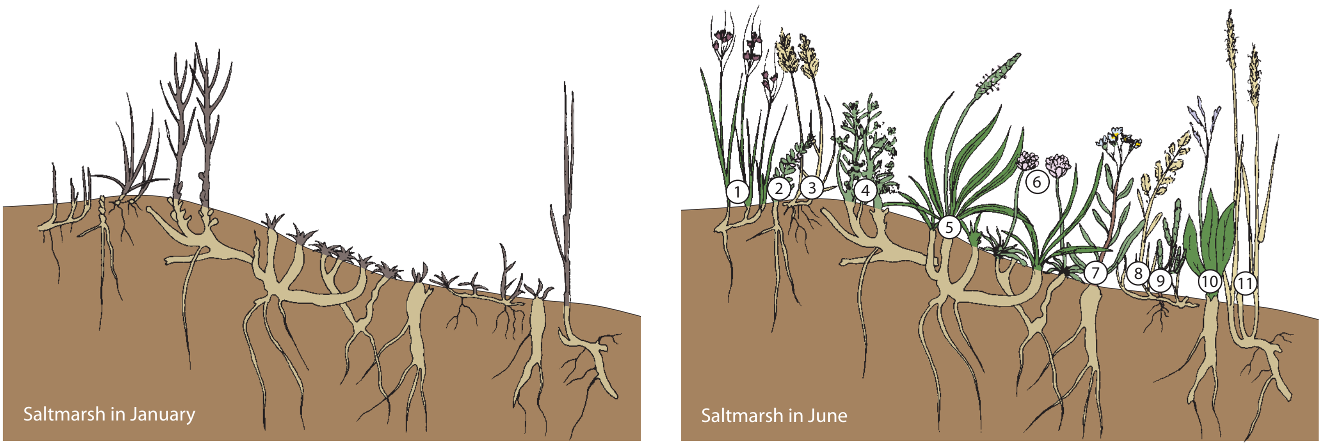
An example of limited impacts and rapid recovery is shown by studies of saltmarsh oiled during the 1996 *Sea Empress* spill. The light crude extensively covered marsh plants in a number of areas within Milford Haven, Wales, but saltmarsh surveys found few detectable effects, with most oiled plants having survived and no notable contamination of the sediment. Slight reductions in two species were evident after one year.



Oiled halophyte marsh on the Gulf coast of Saudi Arabia during the 1991 Gulf War spill.

However, moderate and heavy oiling by No. 6 fuel oil in Buzzards Bay, Massachusetts, from the 2003 *Bouchard B-120* barge spill severely impacted the marshes and left persistent residues. Initial attempts to replant some of the affected areas had

Figure 5 *Plants on a British saltmarsh in January and June, highlighting the differences between perennials and annuals*



Source: IPIECA

(a) *Plants on a British saltmarsh in January, showing parts protected by soil and naturally dead vegetation (dead vegetation is shown in grey).*

(b) *The plants in June, showing parts susceptible to oil—leaves, stems and flowers. Annual plants such as* Salicornia *are particularly susceptible because, unlike most of the perennials, they do not have substantial underground systems with protected buds and food reserves. Moreover* Salicornia *does not have a persistent seed bank in the soil, so if killed before seed is set, recolonization will depend upon dispersal of seeds from elsewhere.*

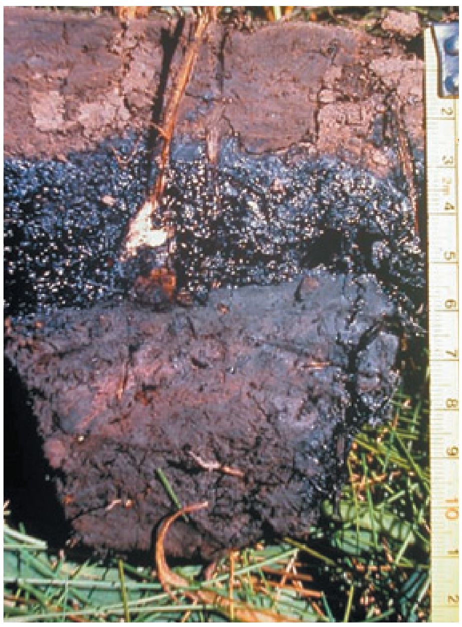
Key

1. Juncus
2. Glaux
3. Festuca
4. Artemisia
5. Plantago
6. Armeria
7. Aster
8. Puccinellia
9. Salicornia
10. Limonium
11. Spartina

mixed results, and significant bare patches were still present after more than two years. Estimates of recovery time were longer than 10 years.

While studies of oil spill impacts on saltmarshes have largely concentrated on the vegetation, impacts on marsh fauna, particularly crabs and bivalves in the sediment, have been carried out after some spills. See the section on sedimentary shores (pages 22–26) for descriptions of effects on intertidal sediment life.

Saltmarshes typically develop in areas that are sheltered from wave exposure and tidal currents, so the natural removal of oil can be slow, particularly if it is viscous or if it penetrates into the sediment. In some marshes oil can also be buried by the deposition of sediments. Not only is oil beneath the sediment surface protected from removal by water movement, but biodegradation is generally slow because saltmarsh sediments are typically anoxic (depleted of oxygen). In one study, oil that had been buried in a marsh for 22 years was still recognizable as heavy fuel oil, albeit highly degraded (see photograph, right). Studies of marsh sediments contaminated by the 2010



Dr Jenifer M. Baker

Photograph of oil on a Spartina saltmarsh in Milford Haven, Wales, 22 years after a fuel oil spill contaminated the marsh. A hydrocarbon analysis found that it was still recognizable as heavy fuel oil, albeit highly degraded.

Macondo incident have shown persistence of the heavier oil fractions, but also show rapid degradation of lighter fractions by sulphate-reducing bacteria present in anoxic conditions, and by oil-degrading fungi. Persistence is typically greater in sediments with a higher organic matter content.

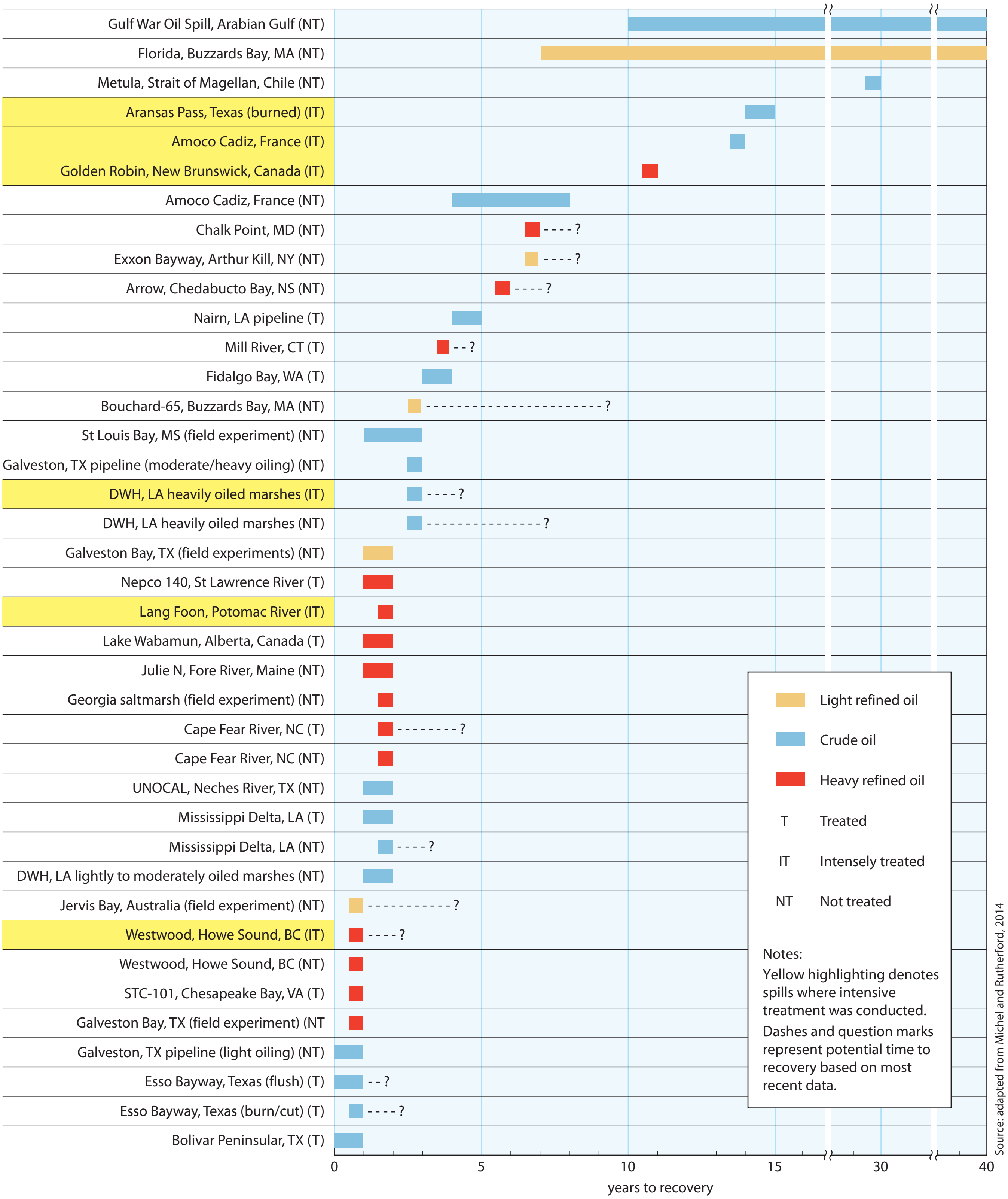
On the ESI scale, saltmarshes are therefore given the highest classification (ESI 10). While all marshes are so ranked, natural removal processes can still vary between marshes. Those found along the banks of estuarine channels will be subjected to water movement that can help to remove oil, while those at the back of large tidal flats will not. Persistence of oil is the main factor causing long-term impacts in marshes, other factors being intensive treatments or species with poor recolonization potential.

In a review of 32 oil spill studies (including some experiments), the estimated recovery of impacted marshes was within two years for approximately half the studies, within ten years for approximately a third, and more than ten years in six cases. In three of those six cases the slow recovery was due primarily to intensive treatment (see *Shoreline treatment and restoration* on pages 36–44) but the three longest-term impacts, which are still evident, are due primarily to persistent oil. See Figure 6.

The 1974 *Metula* spill in the Magellan Strait, Chile, resulted in thick oil deposits on a marsh, and those deposits are still visible in some areas. The thick residues resist natural physical removal processes and biodegradation by bacteria, but saltmarsh seeds are germinating in some cracks and the slow growth of the plants in the cold climate is gradually helping to break it up.

The 1969 *Florida* barge spill in Buzzards Bay, Massachusetts, deposited No. 2 home heating oil in a marsh dominated by cordgrass (*Spartina alterniflora*), fiddler crabs and clams. There was a high mortality of all three in the most heavily-oiled areas, followed by a gradual recovery as the toxicity of the sediment reduced. Twenty years after the spill the saltmarsh appeared visually the same as in non-impacted areas, but high concentrations of oil remained in anoxic marsh sediments in some areas. Recent studies have shown that high concentrations are still present in a few locations, 8 to 20 cm below the surface, and that fiddler crab do not burrow into that oiled sediment layer, suggesting avoidance behaviour.

Figure 6 *Summary of marsh recovery times for a range of oil spills and field experiments*



Right: brackish water marsh on the River Plate near Buenos Aires, Argentina in 1999, after being oiled during the Estrella Pampeana *spill. The photographs below show the effects of the intensive physical clean-up and the rapid regrowth of the marsh, from the same viewpoint, in January, April and October 1999 and November 2000 (22 months later).*

Much of the rapid growth, however, was of opportunist species rather than the natural community, which had not fully returned when last surveyed in 2003. Nearby marsh areas that were similarly oiled but left alone showed rapid recovery and no differences compared to unoiled reference areas in 2002.

January 1999

April 1999

October 1999

November 2000

The 1991 Gulf War spill contaminated a substantial area of extremely sheltered broad sediment flats colonized by long-lived slow-growing halophyte marsh plants, burrowing crabs and algal mats. Oil penetrated the sediments via the crab burrows, and recolonization of halophytes and crabs has been slow. Recovery could take many decades and restoration is ongoing (see page 44).

Studies of the impacts on saltmarshes from the 2010 Macondo oil spill are ongoing, but initial studies have described some mortality of marsh plants in areas that were oiled. Some of the most heavily oiled marsh has been treated to remove residues that might otherwise be persistent (see page 40). Some studies of saltmarsh killifish in Louisiana have found evidence of sublethal effects on tissue morphology, although another study found no difference in the species composition, abundance or size of saltmarsh fish at oiled and unoiled sites two to three years after the spill.

Mangroves

Mangroves are biologically diverse and productive habitats present in wave sheltered shorelines of the tropics and sub-tropics. The mangrove ecosystems are dominated by mangrove trees (or shrubs) that create the main physical structure within which many other species live. They can form narrow fringes along the edges of estuaries and other sheltered marine inlets or extensive forests on the low-lying land of deltaic systems. The marine communities within mangroves typically include a variety of algae and invertebrates attached to the roots and trunks of the trees and bushes, other invertebrates burrowing in or living on the surface of the muddy sediments, fish living in the channels or moving in with the tide to feed in the mangrove, sea snakes and other reptiles and many species of wetland birds that feed on the life in the sediment and water. The mangrove canopy also provides habitat for a large variety of mammals, birds, other vertebrates, insects and plants. Furthermore, as mentioned in the introduction, mangroves provide many other important ecosystem services, dependent largely on the stable structure created by the root system.

IPIECA

Far left: dense black mangrove in Oman, showing pneumatophores (breathing roots).

Near left: cross-section of pneumatophores, showing spongy aerating tissue.

Mangrove trees and shrubs are adapted to living in saltwater, and their roots are further adapted to cope with the anoxic conditions that are typical of the muddy sediments in which they grow. As the roots cannot get sufficient oxygen through the sediment for their physiological functions, they have evolved to develop aerating structures above the sediment surface. A number of different forms have evolved, including the prop roots of red mangroves (*Rhizophora*), the pencil-shaped pneumatophores of black mangroves (*Avicennia*) and the much larger peg-shaped pneumatophores of *Sonneratia* mangroves. Spongy aerating tissues in these structures connect to small surface pores called lenticels. If these pores are blocked, the roots can become starved of oxygen and the plant will suffer. If a large proportion is blocked the plant may die. An early sign of stress is loss of leaves (defoliation).

A spill of persistent oil entering a mangrove has the potential to smother the mangrove breathing pores and can also have toxic effects on the roots. Lighter products may have less impact through smothering, but can be more acutely toxic. Case studies from numerous mangrove spills have documented these impacts and suggest that contamination of more than 50% of a tree’s breathing root surfaces is likely to result in death of the tree. Following defoliation, the decay processes, which can happen very quickly in those hot humid environments, then result in the

Above left: oiled prop roots of red mangrove, following the 2005 pipeline spill into the Coatzacoalcos river, Mexico.

Above centre: defoliated mangroves in Guanabara Bay, Brazil, resulting from contamination by an oil spill five months earlier.

Above right: remains of a mangrove in Mombassa Harbour, Kenya, in 1991; the mangrove was oiled by a fuel oil spill in 1988, and has since grown back.

collapse of the affected trees and the loss of habitat for resident species. In addition to impacts on the mangrove trees and bushes, the invertebrates living in the surface sediments and on the mangrove roots will also be vulnerable. Crabs, other crustacea and snails are particularly sensitive and their populations may be depleted.

The sheltered conditions of mangroves, particularly in their interior, mean that once oil has entered it is likely to remain, unless, by chance, it passes through during a period of high tide. More often it becomes concentrated on berms or upper intertidal areas within the mangrove and in pools in shallow hollows in the sediment surface. It is also likely to stick to the rough surfaces of any mangrove roots that it touches. Mangroves sediments are typically also home to large numbers of crabs, mudskippers and other species that live in burrows, and these burrows can provide a pathway for oil to penetrate into the sediment. Oil is therefore likely to persist in mangroves and may remain for many years, particularly where it has become buried in anoxic muds. Oil degradation in the surface sediments, however, can be rapid in the tropical conditions and natural recolonization by mangrove seedlings (called propagules) may begin within a year where oil deposits are relatively light. However, mortality of seedlings may be relatively high, and growth may be slow where subsurface toxicity is still high. Recolonization of associated species will take place alongside that of the trees, but growth of trees to a size that supports diversity associated with a mature canopy (e.g. nesting birds, etc.) may take many years.

On the ESI scale, mangroves, like saltmarshes, are given the highest classification (ESI 10). While all mangroves are given this ranking, the sensitivity of mangroves to oiling and the potential for natural removal can still vary. The substrata in some mangroves is relatively sandy, with greater oxygen permeability, so that the mangrove is less reliant on its aerial roots, and mangroves found along the banks of channels will be subjected to water movement that can help to remove oil. The highest mortality of trees after a spill has often been just inside the margins of the mangrove, where the oil has been concentrated and not removed by the greater water flow at the edge.

Crude oil from the 1986 Bahia las Minas spill oiled more than 85 km of coast, including areas of coral reef (page 35), seagrass beds and mangroves. The oil caused substantial loss of red mangrove trees along 27 km of coast and a consequent reduction in the cover of all major groups of epibiota that grow on the red mangrove prop roots. Restoration to accelerate recovery of the mangrove was initiated and was fairly successful but took many years to recreate all the ecological services of the mature habitat (see *Restoration of shorelines* on page 43).

The 2006 *Solar* spill in Guimaras, Philippines, resulted in oiling of mangroves with a heavy (No. 6) fuel oil. Severe mortality of mangrove trees left significant areas of the interior deforested and high concentrations of oil were found in the mangrove sediments. Oil concentrations declined rapidly in surface samples and density of seedlings gradually increased, except where dead trees were being extracted.

Coral reefs

Coral reefs are predominantly subtidal habitats, but many fringing reefs include extensive coral flats that are partially uncovered during low tide periods. They tend to be dominated by a few robust species of hard corals that can withstand periods of emergence, but these provide habitats for large numbers of other species. An oil slick may therefore temporarily smother emergent corals and have acute toxic effects, but it is unlikely that the oil will persist within the reef habitats. Shallow subtidal areas of fringing reefs are highly productive and biodiverse, and will be both vulnerable and sensitive to dispersed oil. Concentrations of oil may be elevated in these shallow waters due to the action of the surf and oily water washing off the shore. However, these areas are often difficult to study.

In 1986, at the Baha Las Minas oil terminal in Panama, a large spill of crude from a storage tank impacted mangroves, fringing reef flats and associated seagrass beds on the flats. Hard and soft corals, coralline algae and animals living in the algal turf were impacted, primarily from direct physical contact with oil along the reef edge. This was followed by increases in algal mats over the dead corals. Recovery to pre-spill conditions of coral and algal cover occurred within one year, but recovery of some of the associated animals took longer. Areas of seagrass bed and densities of mantis shrimps declined and were still low after five years. Chronic oil contamination from persistent residues in nearby mangroves was shown to have continuing sublethal impacts on coral growth after five years.

Coral reefs are discussed further in the IPIECA-IOGP Good Practice Guide on the impacts of oil spills on marine ecology (IPIECA-IOGP, 2015a).

Below left: aerial view of a coral reef flat in the Philippines. Emergent corals and the very shallow reef habitat will be both vulnerable and sensitive to floating and dispersed oil.

Below right: the 1986 Baha Las Minas spill in Panama oiled fringing reef and other shoreline habitats within areas that were already being studied by researchers from the Smithsonian Tropical Research Institute.

Carl Hansen/Smithsonian Institute

Shoreline treatment and restoration

Persistent oil is the primary cause of slow recovery, and it is therefore desirable to remove oil contamination from shorelines as quickly as possible. However, experience from past spill responses has shown that it is possible to do further damage with inappropriate or overly invasive treatments. It is, unfortunately, often the case that shorelines with the greatest potential for oil persistence are also the ones most sensitive to many physical clean-up techniques. However, many lessons have been learned and modern approaches, including techniques, technology, management and planning for oil spill response, are highly advanced. The continuous requirement for trained and experienced personnel is also being addressed, and today's contingency plans include training regimes as an essential component. Although many challenges still remain, the appropriate responses can greatly reduce the impacts of an oil spill.

This section summarizes some of the environmental issues that need to be considered in a shoreline response, and outlines current approaches for tackling them. Every shore and spill has different features and challenges, and there is a need for an objective decision making process, including net environmental benefit analysis (NEBA) (see below) and shoreline clean-up assessment technique (SCAT) surveys (see page 45).

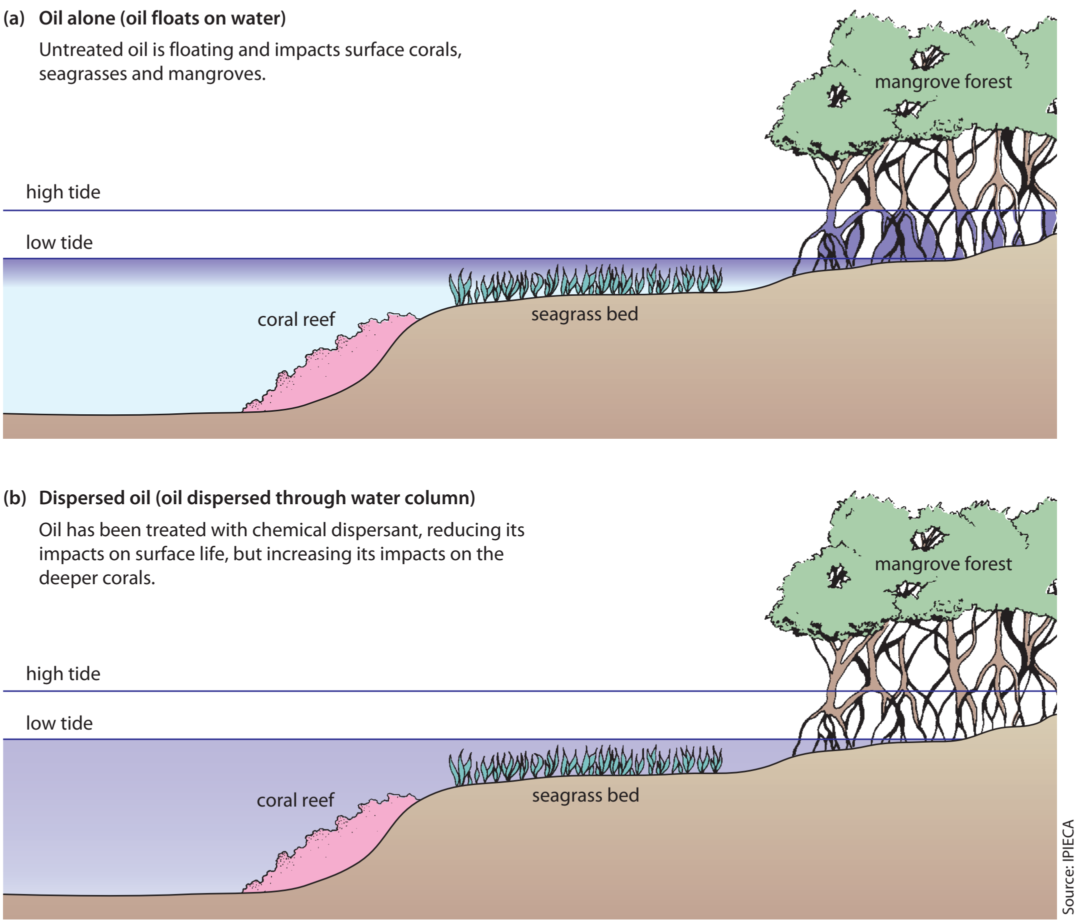
Net environmental benefit analysis

During the response to an oil spill, many operational decisions are made by the response centres to select actions that will remove or treat oil and reduce damage to affected resources. Some of those actions can have significant implications for the environment and for socio-economic resources. NEBA is a widely used and structured assessment process that objectively considers the potential benefits and impacts on all resources from one or more clean-up/treatment options, and compares them with the potential outcome if no response action is taken. There is no standard methodology and the scope of the process may only consider ecological resources, but it can also be expanded to include a wide range of amenity, social, economic, archaeological and other natural environment resources.

Sometimes this can result in decisions that require a trade-off between different environmental and socio-economic concerns. The key objective is to minimize long-term impacts by identifying situations that could result in persistent oil and evaluating response options that reduce that risk. The section on fate, persistence and natural removal of oil (pages 6–13) highlights the fact that while natural processes can remove oil fairly quickly from many shoreline situations, leaving the oil for that long may be unacceptable to managers of affected economic resources. Another typical assessment might compare the advantages and disadvantages of a response in an oiled saltmarsh that is used by large numbers of birds, balancing the risks of damage to the marsh against the risks of more oiled birds, and looking for an option that reduces both sets of risks over the long term.

Recognition of the potential for severe impacts and long-term persistence of oil in mangroves has stimulated an approach to spill response that sometimes recommends the application of chemical dispersants onto oil approaching a mangrove. In some situations, where the oil cannot be stopped from entering the mangrove, it is suggested that the use of dispersant products may reduce the overall level of impact even if the water depth is less than the normally recommended limit of >10 m and there are sensitive resources in the shallow subtidal zone. This approach was tested in the 1984

Figure 7 *Two oil spill situations studied in the 1984 TROPICS experiment in Panama*



TROPICS field trials, in Panama, where three sites (each with an area of 1000 m^2), comprising fringing mangrove with closely associated seagrass beds and coral reef, were treated with fresh oil, dispersed oil and no oil, respectively (see Figure 7). Detailed studies of the oil fate, impacts on each habitat and their recovery were carried out. The results of this now 30-year-old study showed long-term persistence (up to 25 years) of hydrocarbons in the undispersed oil site, but no detectable contamination in the dispersed oil site after three years. There was severe mortality of mangrove trees (still evident after 10 years) and apparent long-term impacts on growth of seedlings (beyond 25 years) in the undispersed oil site, but very limited and short-term impacts on mangroves in the dispersed oil site. There were short-term (one year) declines in coral cover, other coral invertebrates and territorial fish at the dispersed oil site, but these were followed by increases at all sites. Applying a NEBA concludes that chemically-dispersed oil may have more shorter-term impacts on shallow subtidal resources than undispersed oil in a mangrove but less overall environmental impact. However, dispersants should not be applied in situations where the exchange of water is poor.

For a full discussion of the methodologies involved, see the IPIECA-IOGP Good Practice Guide on the use of NEBA in response strategy development (IPIECA-IOGP, 2015b).

Typical clean-up options

A large number of shoreline treatment methods ('treatment' is used here to include all clean-up methods) have been tried, tested and adapted to particular circumstances. The *References and further reading* section (pages 48–53) includes details of oil spill clean-up manuals containing more detailed descriptions of the available options. The effectiveness and consequences of any shoreline treatment method are, to a large extent, determined by the way that it is applied and the scale of the operation. Many potential impacts are associated with access, waste disposal and disturbance to wildlife, and these are relevant to all of the active response methods listed below. Trampling and use of heavy vehicles and machinery, particularly in soft sediments, marshes and mangroves, can cause physical damage, compaction of sediments and damage to roots. Trampling can also push oil deeper into the sediments and prolong its persistence. A number of studies have described such impacts, most notably the long-term physical disturbance and erosion resulting from aggressive clean-up of the Ile Grande marshes following the 1978 *Amoco Cadiz* spill, while oiled but uncleaned marshes recovered much more quickly. More recently, clean-up activities after the 2006 *Westwood Anette* spill in British Columbia trampled estuarine marsh and also delayed recovery. Various clean-up manuals provide guidance on managing numbers of workers, access routes, appropriate vehicles, trafficability of sediments, minimizing and managing waste, minimizing wildlife disturbance and other management good practices. Another important aspect of such guidance is when to stop cleaning: defining end points that provide effective removal of oil without excessive impact and promoting natural recovery. The IPIECA-IOGP Good Practice Guide on shoreline clean-up techniques provides further details (IPIECA-IOGP, 2015).

The photographs below provide examples of damage caused to a mangrove by trampling (left) and the poorly managed use of heavy equipment on a river shore (right) following two oil spill incidents.

Trampled mangrove breathing roots during the 2005 Coatzacoalcos oil spill, Mexico. Clean-up crews removed some oily debris, but caused additional damage to the mangrove in the process.

Peter Taylor

Over-zealous use of heavy vehicles during clean-up of 1989 Worthy *spill.*

Examples of the main clean-up methods used, their benefits and potential impacts on ecological resources are described below:

- **Leave alone for natural weathering:** no clean-up activity—usually chosen because it is considered that the impacts of clean-up would outweigh the benefits of removal. This approach is most often applied to lightly oiled shorelines. The natural removal of the oil should be monitored to ensure that it does not have a greater impact than expected. The primary benefit is that it causes no further impact associated with clean-up, but the potential disadvantages are that the oil may contaminate other resources (e.g. birds) and that it may persist and inhibit recovery of the natural community. Not surprisingly, the apparent lack of a conspicuous response can result in public relations challenges and will require support from key stakeholders.

- **Shoreline protective booming:** booms may be used to deflect oil away from sensitive shoreline habitats or to contain oil on a shore for subsequent recovery. There are a number of practical and operational issues that can limit the effectiveness of these techniques and even cause some impacts. Strong tides and wave action make booming particularly difficult, but in some situations the techniques can result in reduced contamination of sections of shoreline.

- **Use of barriers and berms:** physical barriers, including dams, fences and earthen berms, may be built onshore or offshore to prevent oiling of a sensitive resource (e.g. the entrance to a lagoon) or to trap oil for subsequent removal. It is inevitable that this option will cause disturbance to the shore habitats being built upon, and may potentially lead to impacts on habitats that depend on their exposure to normal tidal movements. When blocking narrow channels it may be possible to include a system to allow water to flow underneath while capturing oil floating on the surface. It is good practice to monitor the conditions in the areas above the barrier, and to re-establish water flow before conditions deteriorate beyond acceptable limits.

- **Non-invasive removal of oil and unattached oiled debris:** removal of bulk oil, without removing or notably disturbing the primary substrata or biota that characterize the habitat, is the primary objective of most shoreline responses. In its simplest form it may require no more than someone with a plastic bag and suitable clothing manually picking up tar balls and oiled debris; however, a number of manually and mechanically operated products, tools and machines have been developed, including various forms of sorbents, rakes, scrapers, suction (vacuum) devices and beach-cleaning machines. Removing bulk oil reduces the risk of oil remobilization and contamination of other resources, and may enhance recovery of the oiled habitat. In many situations these advantages greatly outweigh the disadvantages. However, in other situations there are potentially significant impacts associated with access to the shoreline and the disturbance of wildlife. The use of sorbents also increases the amount of waste material that needs to be disposed of.

- **Sediment reworking and relocation:** these methods enhance the natural cleaning of the sediment due to wave and current action, by tilling, breaking up or relocating contaminated sand, pebbles or cobbles. The latter may involve digging out and moving oiled sediments from the upper shore to further down the shore where there is more wave energy (surf washing). Wave action subsequently remobilizes the sediment and reforms the beach, removing oil in the process. While most of the oil is not recovered, it is typically dispersed or flocculated into the sea

Zengel, S. and Michel, J., 2013

Zengel, S. and Michel, J., 2013

Above: the 2010 Macondo incident resulted in oiling of fringing saltmarsh in some areas of Barataria Bay, Louisiana. A series of marsh treatment field tests were conducted and the results monitored. Access to the affected marsh, without causing additional damage to the muddy sediments, was facilitated by their proximity to channels and the use of shallow draft barges, air boats and walk boards. The tests showed that a combination of manual raking and cutting was effective at removing the mats of oiled vegetation, and aided recovery of the marsh and populations of fiddler crabs. Replanting treated areas with marsh plants further accelerated recovery (see page 43). However, natural recovery was still considered the preferred approach for the majority of oiled marshes from that spill.

and is unlikely to persist. Some oil may refloat and contaminate other resources. If carried out appropriately the potential impacts from habitat disturbance, burial of organisms and temporary increases in siltation are limited, but this will depend on the community present.

- **Physical removal of contaminated substrata or attached biota:** this can include invasive methods that dig or scrape away oiled sediment, or cut/pull up oiled algae or plants. While removal of the oil reduces the risk of oil remobilization and contamination of other resources, removal of the substrata or vegetation has the potential for significant impacts on the habitat and may slow down the recovery of the natural community. Removal of sediment could, in some situations, initiate backshore erosion. If it is decided to reduce contamination in a shorter time than would occur by natural processes, the method employed should remove the minimum amount of sediment or vegetation necessary. Re-nourishment (sometimes termed re-charging) of beach sediments by importing them from elsewhere, usually dredged from offshore, is carried out routinely for some popular amenity beaches, but is not appropriate for all beaches.

- **Flushing and deluge:** these clean-up methods involve pumping and spraying water onto oiled shoreline habitats to remove oil. There are numerous approaches, varying primarily in the volume and pressure of water pumped, and sometimes in the temperature and type of water. A variety of methods may be used to recover the oil that is remobilized by these cleaning methods, but most involve flushing the oil back into the water where it can be more easily contained and recovered. In many situations these methods can be used to mobilize and recover large amounts of oil without having significant impacts on the habitat. However, high pressure or large volumes of water are relatively aggressive and can cause loss of sediment, changes in sediment character through loss of fine particles, burial of organisms, erosion of soft rock surfaces, removal of attached plants and animals, and temporary increases in siltation. Use of hot water to aid mobilization of more viscous oil and use of fresh water rather than seawater may cause additional mortality. Creating trenches, berms or barriers to concentrate oil can also have additional impacts.

US EPA, 2006

US EPA, 2006

Above: in-situ burn of oiled marsh in Louisiana following Hurricane Katrina: (top) 1 hour into the burn; and (bottom) 5 months after the burn.

- **Controlled in-situ burning of oiled vegetation:** in some oiled marsh situations a 'controlled' burn can remove large amounts of oil and allow recovery of the vegetation more quickly than it might have done by natural processes alone. However, the effectiveness of the burn and the potential impacts on the marsh communities can depend on a number of factors, including time of year (winter is best), plant species, soil type (peaty soils are prone to severe damage), water level (>10 cm over the sediment is best) and oil type. Some burns have resulted in rapid recovery, but in other cases the habitats have taken many years to recover. In addition, it can be difficult to control a burn and many have extended far beyond the oiled areas. Controlled burning will also cause mortality of any animals present in the marsh that are not protected by sufficient water or sediment, and it creates large volumes of black smoke that can affect other local resources. An example of an effective in-situ burn that enhanced recovery was carried out after a spill of more than 5,000 tonnes of oil following damage to an oil facility in Louisiana caused by Hurricane Katrina (see photographs above right). The burn removed 80–90% of the gross contamination, and the above-ground and below-ground productivity of the marsh recovered within one growing season.

- **High-pressure washing, steam cleaning and sand blasting:** these are often termed 'polishing' techniques because they are typically used to remove relatively small amounts of weathered oil that is firmly attached to hard substrata, primarily in amenity areas. However, they may also remove biota (e.g. algae, barnacles, lichens) that are attached to the treated area and can

High-pressure washing removes oil but also has the potential to remove living organisms. Whether it is appropriate should depend, at least partly, on the expected rate of recovery. The barnacle-dominated community on the left recovered within less than two years, due to the annual settlement of barnacle larvae from the plankton. The orange lichens on the right showed little or no recovery after 10 years, due to their slow growth and recolonization.

In some situations, treatment of oil residues with chemical agents may be appropriate, particularly where there is high amenity use.

sometimes erode the surface of soft or friable substrata. It is good practice to use sorbents or other methods of recovering the remobilized oil. The ecological benefits are fairly limited except where potentially persistent tar residues cover areas of dry wave-sheltered upper shore rock that could inhibit colonization by biota.

- **Treatment with chemical agents:** a number of chemical agents are designed for use in shoreline clean-up, including surface washing agents, formulations of dispersants and solidifiers. These are also 'polishing' techniques that are mainly used to remove relatively small amounts of weathered oil from hard substrata in amenity areas. They can have similar benefits in wave-sheltered upper shore areas of rock. The remobilized oil may disperse or refloat, depending on the agent. Dispersed oil can create elevated concentrations of oil in nearshore waters and increase penetration of oil into beach sediments, though these are likely to be transitory effects. Surface washing agents, which lift and float oil residues, are generally preferred.

- **Bioremediation:** The main approach to bioremediation is *biostimulation* where nutrients (fertilizers, typically including formulations of nitrates and phosphates) are applied to accelerate the natural microbial degradation processes. If nutrient addition is excessive for the affected area there is the potential for eutrophication (overstimulation of plant growth). Toxicity testing of the bioremediation product may also be appropriate. *Bioaugmentation* involves the addition of oil-degrading microorganisms to an oiled area if the natural populations are considered insufficient. It is used routinely in some contaminated land situations, but has not been effective in shoreline habitats.

The first detailed and structured net environmental benefit analysis was carried out after the 1989 *Exxon Valdez* spill in Prince William Sound, Alaska. It involved an assessment of whether it was appropriate to use intensive shoreline treatment methods to remove oil that had penetrated porous sediments in some shores to depths of up to 1 metre. The proposed treatment involved excavation of oiled shoreline sediments (mainly cobbles and pebbles), washing them in barge-mounted processing systems and replacing them on the beach. However, the NEBA concluded that the process of sediment removal and re-deposition would have considerably greater environmental impacts than if the shorelines were allowed to recover naturally.

Conclusions

From an ecological perspective the best response to enhance recovery is usually the one that removes as much bulk oil as possible without causing any major physical disturbance to the habitat, and then leave it to be cleaned through natural processes. This approach may, however, need to be modified if the NEBA determines that other issues have a higher priority.

Restoration of shorelines

In some situations, damage to a shoreline from oil and/or clean-up may warrant some form of restoration (i.e. additional actions beyond clean-up) to accelerate recovery. Many restoration methods have been tried, tested, developed and adapted, and may be classified as direct or indirect methods. Direct methods involve direct manipulation of the damaged habitat or population. Indirect methods enhance natural recovery of the damaged habitat by reducing other stresses upon it. An alternative approach to restoration may be to offset the impacts by replacing some of the lost services that were provided by the habitat, but in a different place. Generally, this involves the creation of new, or the restoration of already impaired, shoreline habitats (usually wetland) in a coastal area within the same region as the oiled habitat that is considered to be of poor ecosystem value. This is a form of offsetting that is employed in some countries to compensate for impacts on natural ecosystems and the services they provide.

The most successful examples of direct restoration of oiled shorelines have involved saltmarshes and mangroves. There is now considerable experience in wetland restoration in many parts of the world, and a number of techniques have been developed to restore tidal hydrodynamics, stimulate natural recolonization, replant bare ground, prevent erosion and protect the remaining plants. Replanting of oiled areas is not always necessary but is often carried out as part of the whole programme, usually with nursery grown seedlings. This is possible because both habitats are largely dominated by a small number of plant species that are readily propagated. Replanting does not guarantee a successful outcome, particularly if insufficient time has been given for sediment toxicity levels to fall, and may require a progressive programme of planting in stages over many months. There are many examples of restoration programmes in oil spill impacted saltmarshes (e.g. *Amoco Cadiz*, Brittany, 1978; the Exxon Bayway pipeline spill, New York, 1990; and the Chalk Point spill, Maryland, 2000) and mangroves (e.g. Baha las Minas, 1986; the Cartagena refinery spill, Colombia, 1990; and Guanabara Bay, Rio de Janeiro, 2000).

Replanting of saltmarshes following the 1990 Exxon Bayway pipeline spill was carried out to halt surface erosion and further loss of marsh plants. Survival of the *Spartina* seedlings and transplants varied between sites. Three years after planting, the above-ground biomass at two of the three replanted sites was comparable to the biomass at reference sites, but the survival was low at the third site due, at least partly, to wave action from passing vessels.

Replanting of oiled mangroves in Panama, impacted by the 1986 Baha las Minas spill, was initially unsuccessful due to acute residual toxicity of the oiled sediments. A second replanting programme was more successful, but after six years the density of trees was higher in areas that recolonized naturally, and it is possible that the replanting may have been unnecessary. Erosion of replanted or naturally recolonized seedlings could have been reduced with some protective measures.

Rene Bernier, Chevron

Restored mangroves 16 years after planting, following the 1986 Bahia las Minas oil spill

Mangrove seedlings, near Bangkok, Thailand, planted as part of a restoration project following an oil spill

Restoration of halophyte marshes in Saudi Arabia that were severely impacted by the 1991 Gulf War spill is ongoing. It aims to enhance the flow of water to the marsh areas by excavating and unblocking channels, encourage natural recolonization of burrowing crabs by de-compacting the sediment, and assist regrowth of the marsh vegetation by planting perennial halophytes. The restoration activity has had encouraging results but will take many years.

Increased erosion sometimes occurs in areas of shorelines that have been impacted by oil spills and oil spill response activities. A number of restoration techniques are available that are designed to reduce such effects, including 'living shorelines' which generally involves the use of natural and/or artificial breakwater material to stabilize the affected shorelines and diminish wave energy. Some such structures may also provide habitat for shellfish.

Assessment and monitoring of oiled shorelines

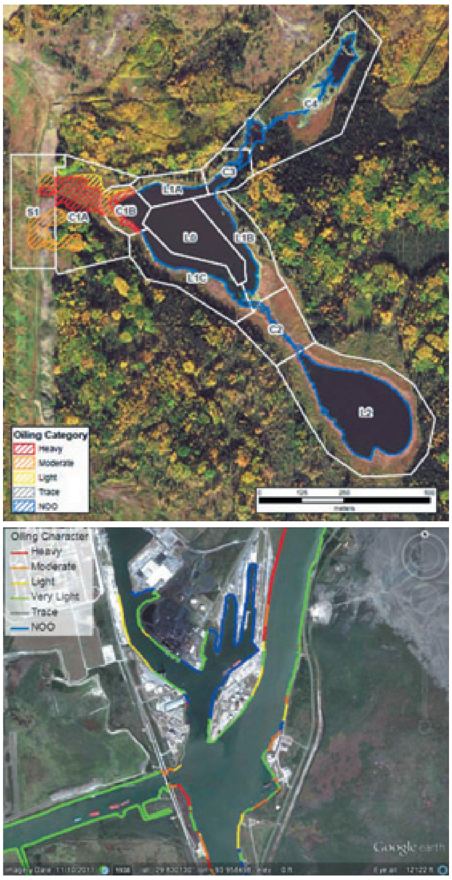
An important part of oil spill response is to describe the fate and distribution of the oil, the effects that it is having and the recovery potential of affected resources. This information is used for: planning treatment activities; assessing the level of contamination in habitats and biota (in particular any that are consumed by humans); assessing the impacts on natural communities and populations of wildlife; management of affected resources; the preparation of compensation claims; and for reassuring the public.

Generic guidance on oil spill damage assessment is given in the IPIECA-IOGP Good Practice Guide on the impacts of oil spill on marine ecology (IPIECA-IOGP, 2015a). Detailed guidance documents are available for some countries and regions, and IMO/UNEP have produced an international guidance document (IMO/UNEP 2009). Some of the key assessment activities relevant to shorelines are discussed below.

Distribution and quantification of shoreline oil

Oil landing on shorelines after a spill is normally very patchy. Some resources may be badly affected, while adjacent or nearby resources may be completely unaffected. Information on the extent and distribution of stranded oil on shorelines is therefore essential for shoreline response planning, and will form the basis of any ongoing studies of impacts and recovery.

Shoreline Clean-up Assessment Technique (SCAT) surveys are carefully structured, systematic surveys of oil thickness, character and distribution on sections of shoreline, using standardized recording forms and trained survey staff. The surveys are normally carried out jointly by environmental and oil spill response surveyors and may be used to monitor the progress of shoreline treatments or natural recovery. In addition to describing the oil distribution, SCAT surveys can also provide valuable records of conspicuous impacts, e.g. dead, torpid or visibly oiled wildlife and bleached algae, which may be transitory. The surveys are also designed to provide information and recommendations to aid treatment decisions for specific beaches and resources. The resultant recommendations may become an important part of a NEBA. For more information on SCAT see the IPIECA-IOGP Good Practice Guide on oiled shoreline assessment surveys (IPIECA-IOGP, 2014).



SCAT maps showing shoreline oiling status: (top) an oiled wetland environment (polygon segments) and lake shoreline environment (linear segments); and (bottom) linear shoreline segments in a commercial waterway.

IPIECA, 2014

Quantification of the exposure of shoreline communities and wildlife to hydrocarbons may be carried out by chemical analysis of water, sediments and biota, with sampling typically carried out at time intervals to provide information on the duration of exposure and to show the progression of changes. It is normally appropriate to use a stratified sampling design that provides unbiased representative data on each resource, at a range of tidal heights and within categories of oiling that may be based on SCAT data. Where possible, baseline samples may be taken from shores in the path of the spill before the oil lands. If pre-spill samples are available they can be valuable as long as they have been adequately stored. Rigorous sampling procedures are required to ensure that there is no contamination from other sources, and the subsequent handling and transport of samples to laboratories for analysis needs to comply with strict chain of custody procedures.

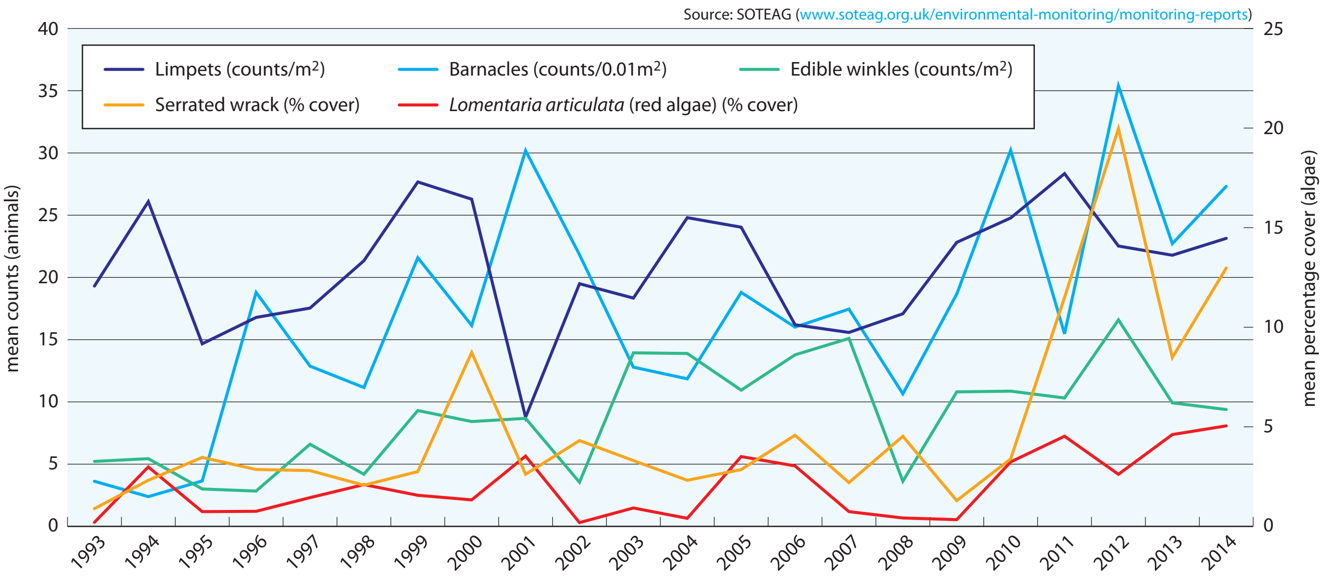
Selection of shoreline biota for analysis of hydrocarbon concentrations in tissues depends on the habitat and the resources of concern. However, bivalves, particularly mussels, if available in sufficient and sustainable quantities, are typically sampled because they are sessile filter feeders and effective bio-accumulators of hydrocarbons. Monitoring their tissue concentrations provides a useful measure, integrated over time and therefore indicative of exposure during the spill and the subsequent return to background concentrations.

Below: fluctuations in the abundance of five selected species recorded over a 21-year period are considered to be natural, reflecting the uncertainty inherent in determining the scale and significance of impacts on biological resources.

Assessing and monitoring impacts on communities and biota

Describing the distribution and level of oil contamination can be expensive and time consuming and the results may require quality assurance and interpretation, but their direct relevance to undesirable effects on the environment is rarely in question. The same cannot be said for many studies of biological and ecological resources. Many of the descriptions and case studies cited in the section on the ecological impacts of oil on shorelines (pages 14–35) use terms that reflect an apparent lack of certainty about the scale and significance of the impact that occurred on a

Figure 8 *Annual fluctuations in the average abundance of selected species**



* Recorded from 15 monitoring sites in the vicinity of the Sullom Voe Oil Terminal, Shetland Islands. All recorded fluctuations are considered to be natural.

biological resource, or even about whether an impact actually occurred. This is because there usually is a lack of certainty. High levels of natural variability (temporal fluctuations and spatial patchiness) and many other potential causes of environmental stress (confounding factors) often make it difficult to interpret biological and ecological data. Guidance documents on impact assessment highlight the often near impossibility of obtaining statistical proof, as well as the real possibility of incorrect interpretation, such as incorrectly detecting an impact or failing to detect an impact that has occurred.

There is limited understanding of the biology and ecology of most marine species, and the accidental nature of an oil spill does not allow for much experimental control. The design of impact assessments and monitoring programmes therefore needs to take account of such factors and learn from previous studies. Wherever possible, assessment studies should determine the baseline condition and natural changes in the shoreline ecology prior to the spill. Whether or not this is achievable, assessment studies should then aim to:

- establish the level of exposure of shoreline communities or resources to oil;
- describe a realistic mechanism (pathway) by which an impact could have occurred;
- describe the impact, with as many datasets from impacted and un-impacted sites as logistically possible;
- describe the recovery process; and
- provide multiple lines of evidence for each of the above.

Evidence from only one or two of those is inherently weak. Published literature on recovery, particularly long-term recovery, is one of the few aspects of oil spill impacts that is relatively limited. Very few studies have been longer than one or two years in duration.

References and further reading

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Useful websites

Interspill: www.interspill.org/previous-events

IOSC: www.ioscproceedings.org/loi/iosc

IPIECA: www.ipieca.org/library

ITOPF: www.itopf.com/knowledge-resources

NOAA: http://response.restoration.noaa.gov/publications

PREMIAM: https://www.cefas.co.uk/premiam/publications

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IPIECA

IPIECA is the global oil and gas industry association for environmental and social issues. It develops, shares and promotes good practices and knowledge to help the industry improve its environmental and social performance; and is the industry's principal channel of communication with the United Nations. Through its member led working groups and executive leadership, IPIECA brings together the collective expertise of oil and gas companies and associations. Its unique position within the industry enables its members to respond effectively to key environmental and social issues.

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