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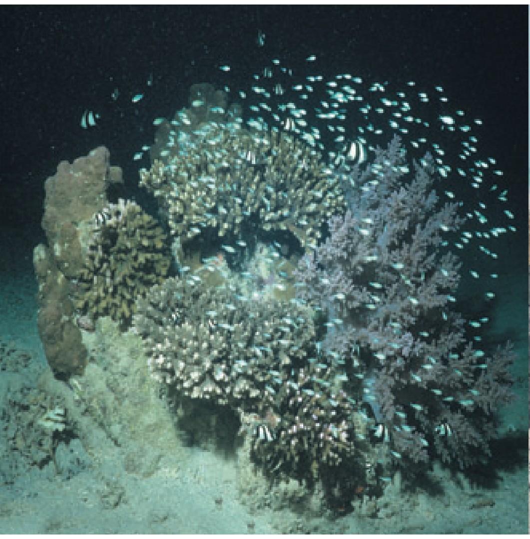
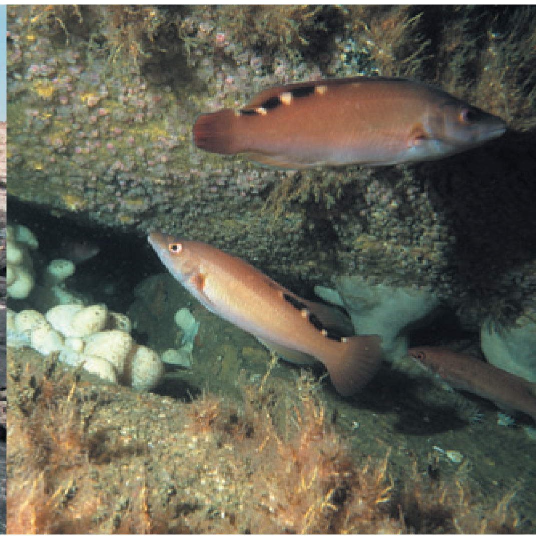
IOGP International Association of Oil & Gas Producers

Impacts of oil spills on marine ecology

Good practice guidelines for incident management and emergency response personnel





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IOGP Report 525

Date of publication: 2015

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All photographs are supplied courtesy of Jon Moore unless otherwise stated.

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.

The original IPIECA Report Series will be progressively withdrawn upon publication of the various titles in this new Good Practice Guide Series during 2014–2015.

Note on good practice

'Good practice' in the context of the JIP 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

Marine ecosystems and oil

The marine environment is a dynamic and diverse network of habitats and species, interwoven by complex physical and ecological processes that interact with humans and their activities at many levels. Marine habitats and their associated communities are often grouped into ecosystems, e.g. the open ocean, deep sea, coral reefs, saltmarshes, rocky shores etc., although they are all connected and impacts on one ecosystem can affect others. Ecosystem structure and function are important features when assessing impacts. The many benefits that humans receive from these habitats and communities are referred to as ecosystem services. The more obvious of these are the fish, shellfish and other foods that we consume, and the recreational or aesthetic benefits we derive from the sea. Additionally, many coastal communities have strong cultural and spiritual ties to the sea. However, there are many other less obvious services.

The marine plankton of the vast areas of open oceans plays a major role in the maintenance of our atmosphere by transferring carbon to the deep sea. The open oceans and deep sea areas are also home to many of the fish that we catch for food, but abundance and productivity increase greatly in shallower waters and closer to coastal areas. Coastal wetlands and some shallow water ecosystems, including saltmarshes, mangroves, kelp forests and seagrass beds, are particularly

Ecosystem services of the marine environment; it is to everyone's benefit that the sea remains clean, productive and healthy.

productive, providing much of the organic material that feeds neighbouring shallow water ecosystems. They also provide food and shelter for young fish and many other species, protect our coasts from storms and flooding, and capture sediments and organic waste that runs off the land. Mangroves and coral reefs also provide building materials, while new pharmaceutical products are increasingly being developed from the enormous diversity of marine species.

Biodiversity (i.e. the variety of life) is, in itself, a valuable feature of these ecosystems as it increases the complexity of the food chains and other ecological processes, which in turn increases their resilience to natural and anthropogenic impacts. Most marine food chains include a range of primary producers (i.e. plants and algae, including phytoplankton, that take their energy from sunlight or organisms that use chemical energy in deep sea vents), bacteria (primarily feeding on dissolved organic carbon), herbivores (zooplankton, seabed invertebrates and some fish), carnivores, scavengers and parasites (a wide range of animals) and decomposers (particularly bacteria and fungi). Biodiversity and other ecosystem services are reflected in the national and international regulatory regimes that recognize the need for conservation and protection of important habitats and species. This includes the designation of protected areas.

Mineral oils (i.e. petroleum) derive from plant material and animals that originated millions of years ago, and have been modified over time by heat and pressure underground. In many locations, these underground reservoirs of oil are connected to the surface by geological features such as faults or salt domes, and in some areas natural seeps occur through the seabed. These naturally occurring oil seeps have been present in the world's oceans for millions of years, and marine organisms have evolved to develop molecular mechanisms which enable them to biodegrade and detoxify these substances and incorporate them into the food chain. Natural background levels of *petrogenic* (see Box 1 on page 7) hydrocarbons exist in seawater and seabed sediments, and are greater in some areas than others, depending on the prevalence of oil seeps. Since the industrial revolution these natural levels have been added to by aerial emissions, land run-off and inputs from marine transport. The US National Research Council estimated that about half of the oil entering the world's oceans every year has anthropogenic origins, the remaining half occurring naturally from seeps.

Large oil spills are rare but can result in significant and long-term adverse impacts. The scale of spill impacts can range from minimal (e.g. following spills of lighter oils in the open ocean) with no or little detectable effect lasting only a few hours or days, to significant (e.g. bulk amounts of heavy oils entering sheltered wetland habitats) with longer-term effects. Larger spills have the potential to cause greater damage than smaller ones, but the level of impact varies considerably depending on the oil and incident type, local conditions (such as season, weather and location) and resources present.

The development of oil exploration in polar and deep water environments brings a number of challenges to oil spill response and science. Plants and animals in cold water ecosystems tend to be longer-lived and slower-growing than those from warmer climates and waters, and the rate of many biological processes is relatively slow. Persistence of oil, a major factor in habitat recovery, may also increase with higher latitudes. It is therefore often assumed that recovery from oil spills will take longer, but this depends on many factors. Studies have shown that microbes present in cold water ecosystems can degrade oil rapidly when no other limiting conditions are present.

Oil spill response efforts are designed variously to remove oil contamination, enhance its biodegradation and prevent it reaching the more sensitive parts of the ecosystem, but can cause further damage to the environment. In some situations there is a need to consider trade-offs and assess the net environmental benefits of response options. Science underpins environmental risk assessment and management of operations, including oil spill response decisions. Our knowledge is based on the large body of evidence from studies of past spills and experimental research.

Purpose of this document

The purpose of this document is to provide an overview of how oil spills can impact marine ecological resources and functions, and how quickly those resources and functions can recover. 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 in the marine environment*, describes the properties of mineral oils and physical processes that spilled oils go through that are relevant to marine ecological impacts. Emphasis is placed on the properties and processes that affect oil persistence, as they are most likely to influence long-term effects.

The section on *Ecological impacts and recovery* provides a general description of the mechanisms and factors that typically affect the impacts of oil spills on marine resources and their rates of recovery.

The third section, *Impacts of oil spills on marine life and associated wildlife*, describes some of the more common impacts of oil spills on life forms associated with different ecosystems, and includes references to relevant case studies.

The section entitled *Managing oil spill response and potential impact* considers current good practice in spill response and how it is designed to minimize environmental damage (i.e. maximize the net environmental benefit of response techniques).

The fifth section, entitled *Oil spill damage assessment—key activities*, summarizes some of the fundamental approaches and requirements of a damage assessment, and the follow-up monitoring necessary to describe recovery.

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

The IPIECA-IOGP Good Practice Guide (GPG) series includes a number of other titles which may also be of interest to the reader, in particular the GPG entitled *Impacts of oil spills on shorelines* (IPIECA-IOGP, 2015a) which provides more detailed discussion on the fate and effects of marine oil spills on shoreline resources. Other titles with direct relevance cover subjects such as net environmental benefit analysis (IPIECA-IOGP, 2015b) and the use of dispersants, both on the sea surface (IPIECA-IOGP, 2015c) and subsea (IPIECA-IOGP, 2015d). 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, 2015e).

Oil in the marine environment

Composition and characteristics of oil

Crude oils are complex mixtures of hydrocarbons, with small amounts of other compounds (see Box 1) and elements that typically include sulphur and other trace elements. Refined products, from gasoline to bitumen, are also composed mainly of hydrocarbons, and are produced from crude oil through various refining processes to achieve the desired chemical and physical characteristics.

Hydrocarbons can be classified into many different groups based on their chemical structure, but the characteristics that are most relevant to their fate in the marine environment are their molecular weights and boiling points (usually closely related), and their water solubility and bioavailability (also closely related). The compounds with the lowest molecular weights usually have the lowest boiling points and are volatile at low environmental temperatures. Many of these compounds may display acute toxicity (see Box 2 on page 9), but on the surface of the sea or shore they evaporate so quickly that their contribution to marine impacts is generally small. If released in deep water they have a greater contribution to toxicity, though these low molecular-weight compounds generally biodegrade rapidly. At the other end of the scale, high molecular weight hydrocarbons (e.g. asphaltenes, a major component of bitumen) have a high boiling point, are resistant to biodegradation and are very persistent. They may also be chronically toxic but are usually much less biologically available due mainly to their very low solubility in water. In between these two extremes are a wide range of hydrocarbons, many of which have the potential to cause biological impacts.

Box 1 *Oil types and groups*

Hydrocarbons: true hydrocarbons contain only carbon and hydrogen. Crude oils typically also contain a proportion of other organic compounds that are mainly carbon and hydrogen but with some nitrogen, sulphur and oxygen. For the purposes of this document the term hydrocarbon is used generically to include all of these organic compounds.

Aromatic hydrocarbons: responsible for most of the toxicity in oil, and have one or more benzene rings:

- Benzene, toluene, ethylbenzene and xylenes (BTEX compounds) have one ring and are relatively soluble in water, but are also volatile (very low boiling point).
- Polycyclic aromatic hydrocarbons (PAHs) have two or more rings:
  - naphthalene and alkyl-substituted derivatives are two-ring compounds, and have moderate water-solubility and volatility;
  - three- and four-ring compounds are slightly water-soluble and are not volatile (high boiling point); and
  - compounds with five or more rings are effectively insoluble in water and have a high boiling point.

Group 1 to 5 oils: the oil industry categorizes oils into five groups based on their specific gravity, from Group 1, with very low (<0.8) specific gravity (e.g. kerosene) to Group 5, with very high (≥ 1.0) specific gravity (e.g. bitumen). This grouping is useful when discussing fate and persistence of oil spills.

Petrogenic, pyrogenic and biogenic hydrocarbons: derived directly from mineral oils, the incomplete burning of fossil fuels and biological processes, respectively.

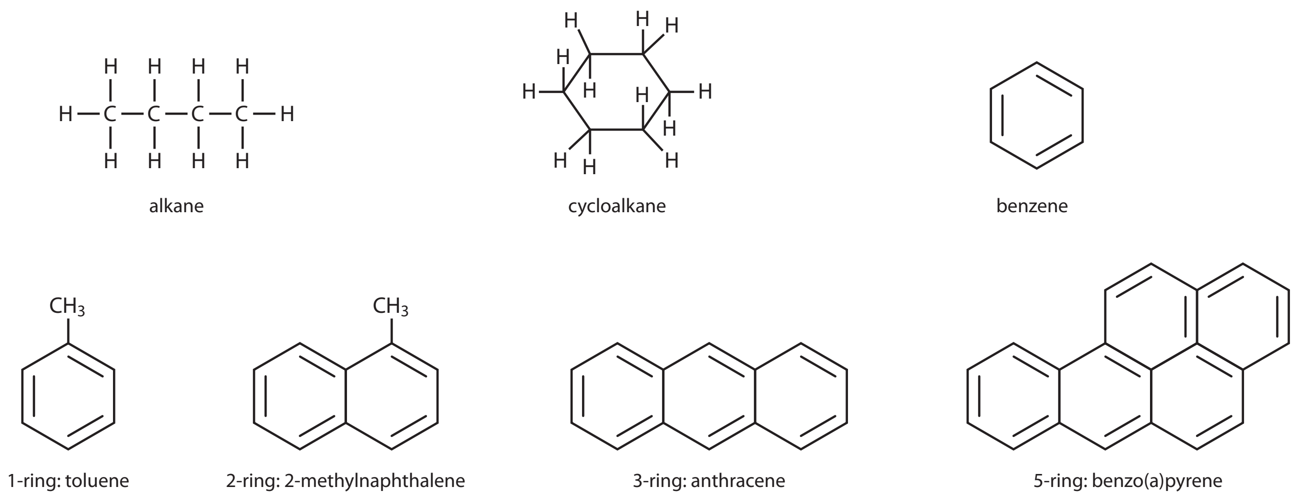
Assessing the toxicity of hydrocarbon compounds (see Box 2 on page 9) is not straightforward and is influenced by many factors. However, aromatic hydrocarbons, particularly PAHs, tend to have greater toxicity than other hydrocarbon groups. Their concentrations (as total PAH or individual PAH compounds) are often analysed and monitored in water, sediments or animal tissues as an indicator of toxic contamination. Many low molecular weight aromatics have relatively high water solubility and therefore biological availability, but also low persistence. These can be responsible for most of the narcotic effects that cause acute impacts. Of greater concern are some of the middle molecular weight PAHs that are less soluble but more persistent, and so highly toxic that the small amounts that become biologically available have the potential to cause longer-term chronic impacts. Even high molecular weight aromatic compounds, such as asphaltenes, could cause some chronic effects in an organism if it is closely associated with a tar residue for long enough.

PAHs can enter the marine environment from a number of sources, not just from oil spills. Atmospheric deposition of particles derived from the incomplete combustion of coal, oil and many other materials results in significant inputs of *pyrogenic* PAHs to natural ecosystems.

The properties of a whole oil are a function of its constituent compounds. The key physical properties are density (or specific gravity), viscosity, pour point (the temperature above which it will pour); and the key chemical properties are the aromatic, wax and asphaltene content. Light oil products have low density and viscosity and often high aromatic content, so are often acutely toxic but unlikely to be persistent in most environments. Heavy crudes and fuel oils have a relatively high density and viscosity and are much more likely to be persistent, but can still be toxic depending on their composition. All of these properties are likely to change once an oil has been spilled (see *The fate of oil* on pages 9–14).

Definitions of terminology related to toxicology are presented in Box 2 on the following page. However, it should be noted the main environmental effects from oil spills are typically due to the physical coating or smothering of plants and animals, particularly on shoreline habitats, rather than through the oil's toxicity.

Figure 1 *Examples of the structure of chemical compounds in crude oils*



Box 2 *Toxicology*

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 potential or capacity of a material to have adverse effects on living organisms; aquatic toxicity is the effect of chemicals on aquatic organisms. Since any substance has the potential to be toxic, the specific organism and its exposure to the substance should always be considered.

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. Acute and chronic effects may be of low or high magnitude, but chronic often implies low magnitude and may be subtle and difficult to detect.

Bioavailability is the extent to which a chemical is available for uptake into an organism and, with respect to oil spills, is usually closely related to both the display of toxicity and the rate of biodegradation.

Bioaccumulation occurs when an organism absorbs a toxic substance into its tissues at a rate greater than that at which the substance is lost.

Lethal and sublethal effects: a lethal effect results in the death of an organism, while a sublethal effect results in a reduction of biological function or health, e.g. its growth, ability to reproduce, or the condition of its skin.

Biomarker: this term has two very different uses, both of which are relevant in this document:

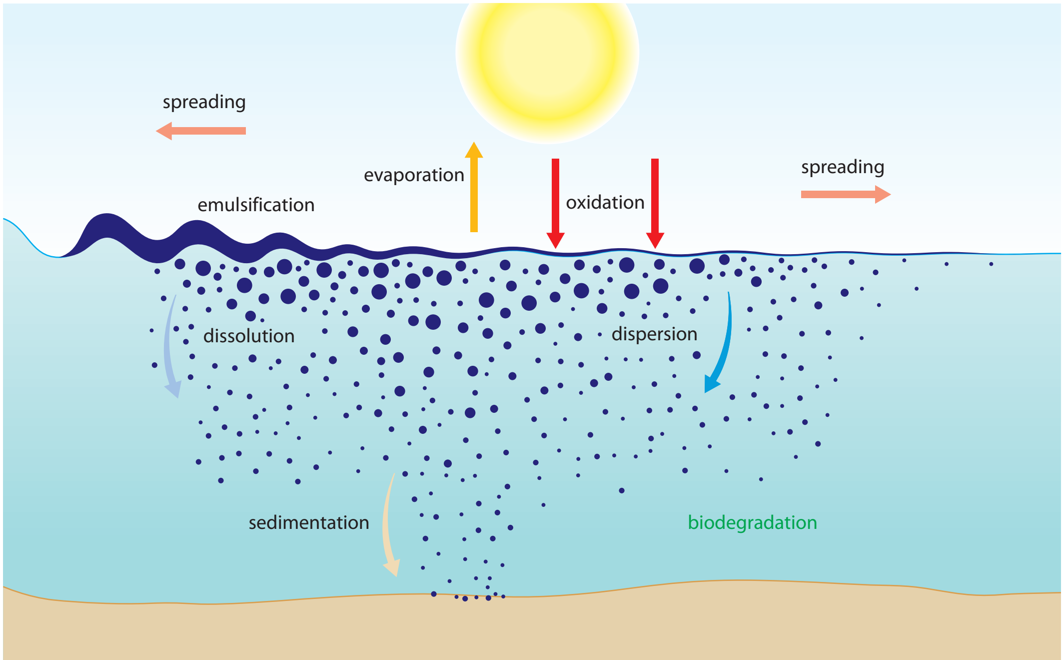
i) a specific sublethal biochemical or physiological measurement which is used as an indicator of exposure to a contaminant (e.g. PAHs) in an animal; or

ii) a hydrocarbon compound found in oil that was originally produced by living organisms and is mostly unchanged (sometimes called a 'molecular fossil') and is used in hydrocarbon analysis to uniquely characterize (i.e. 'fingerprint') the particular oil.

The fate of oil

As soon as oil is spilled into the marine environment it becomes subject to a number of natural processes, known as 'weathering', that quickly and progressively change its character and redistribute much of it into other parts of the environment. The importance of each process on the fate of the oil depends on where the spill occurs (i.e. the environmental conditions) and the type of oil (i.e. the chemical and physical properties described on pages 7–8). The mechanism and scale of ecological effects are greatly influenced by the fate of the oil. The main weathering processes are described on pages 10–14.

Figure 2 *Oil weathering processes*



Evaporation

Most fresh oils contain a proportion of low molecular weight hydrocarbons that have a low boiling point (e.g. alkanes with <12 carbon atoms and the BTEX compounds). When released on the sea or shore, evaporation of these hydrocarbons into the atmosphere will begin immediately, influenced by ambient temperature and air movement. This process progressively increases the viscosity of the spilled oil, but also reduces the volume and acute toxicity of the remaining oil. If the oil remains at the surface for many hours or days, this weathering process can leave a sticky residue with a relatively low toxicity. The proportion of oil remaining can vary from almost none to almost all of the oil originally spilled. For example, 10 tonnes of gasoline spilled into a tropical sea on a calm summer day (25°C) would evaporate completely in less than three hours, and would take only six hours to evaporate in an Arctic sea on a calm winter day (5°C); however, in the same conditions, a heavy fuel oil (e.g. Bunker C) would have lost only 20% and 15% of its volume, respectively, to evaporation after four days (source: NOAA, 2015).

Spreading and movement

If an oil is spilled onto the sea surface it will spread, even without any movement due to tides or winds. The rate of spread depends on the oil's pour point and viscosity: light oils will spread very quickly, at any sea temperature, but heavy oils will spread more slowly and remain thicker for longer, particularly in colder seas where this can also reduce the rate of dispersion (see below). Any surface life or animals that need to come to the surface to breathe will be vulnerable to an oil slick, and the speed and direction of winds and tides will influence how far and wide the slick may spread.

As most oil spread and move they also rapidly start to fragment, resulting in patchiness and the formation of numerous slicks. The oil thickness often becomes very uneven, with scattered areas of thicker oil separated by large areas of very thin oil (sheen) or clear water.

Dissolution

While most hydrocarbons have such a low solubility in water (including seawater) that we can effectively define them as insoluble, some of the smaller aromatic hydrocarbons, such as benzene and toluene, are relatively soluble. Thus, when oil is spilled into the sea, a small proportion dissolves; the amount and rate of dissolution depends on the oil composition and viscosity. This *water soluble fraction* has a disproportionate impact on marine organisms, being more bioavailable than other hydrocarbons and often more acutely toxic. High concentrations of these hydrocarbons are generally limited to the water in the immediate vicinity of the spilled oil, and rapid dilution occurs both vertically and laterally. Biodegradation of water soluble hydrocarbons is generally rapid.

This photograph shows oil from the 1991 Gulf War spill spreading south from Kuwaiti waters under the influence of winds and tides. Much of the oil came ashore in Saudi Arabia, and some of it travelled more than 500 kilometres from the source. Weathering processes progressively changed the oil's character.

Dispersion

Wave action, or other agitation of the oil on (or in) the water, will result in the formation of oil droplets that become mixed into the water column; the greater the agitation the greater the mixing potential. The majority of oil from most spills, whether spilled onto the sea surface, released subsea or deposited onto the shoreline, is eventually dispersed. Larger droplets mixed into the water column quickly resurface, but small droplets are less buoyant and do not resurface; they are mixed horizontally and vertically in the water column. The extent and depth of mixing depends on wave action and water currents. This process can potentially lead to subsurface marine life being exposed to contamination. However, as with the dissolved hydrocarbons, the concentrations of dispersed oil are highest in the immediate vicinity of the release, be it a surface slick or subsurface rising plume, and reduce rapidly as the oil is dispersed further away from the source. In the case of surface slicks, the buoyancy of the oil droplets means that vertical mixing into deeper water is slower than lateral mixing, and elevated concentrations are generally limited to the upper few metres. Dispersed oil droplets have a large surface area and this facilitates biodegradation by microbes (see page 14). The effectiveness of oil droplet biodegradation is a key benefit of using chemical dispersants to enhance the natural dispersion process.

Emulsification

Larger droplets of dispersed oil will quickly resurface and can trap seawater droplets within the surface slick to form a water-in-oil emulsion. Most oils will therefore progressively incorporate water when they are mixed in turbulent conditions (i.e. in moderate or rough seas). The greater the mixing effect, the more water is incorporated into the emulsion, hence the volume of the emulsion increases; in some circumstances the volume of a water-in-oil emulsion can be up to five times greater than the volume of oil originally spilled.

Emulsions may be stable or unstable, and can have very different physical characteristics to their parent oil. Stable emulsions typically have a high water content (sometimes greater than 70%) and are usually highly viscous. They can remain stable for several weeks, and are colloquially referred to a 'chocolate mousse' (or sometimes just 'mousse') due to their consistency and typically reddish-brown colour. The formation of a stable mousse can greatly reduce the rate of dispersion and other fate processes. In calm, warm conditions, e.g. after landing on a beach, a mousse may break down to its constituent oil and water, but some emulsions are highly persistent. An unstable emulsion may decompose after several days, or may persist for as little as 24 hours. Unstable emulsions usually retain the colour of the original oil, i.e. either dark brown or black.

Sedimentation

The fate and effects of dispersed oil are greatly influenced by the amount of suspended solids (fine sediments and other particles) present in the water column. Dispersed oil droplets can bind to suspended solids and change their physical characteristics. Chemically-dispersed droplets may be less likely to bind than physically-dispersed droplets until the dispersant is biodegraded. Deposition of these suspended solids to the seabed can occur, where they may be incorporated into muddy seabed areas with active sedimentation or more widely distributed as a loose aggregation (floc) of oiled particles, or a combination of both. In worst-case situations, where concentrations of oil droplets and suspended sediments are both high, heavy deposition of contaminated particles could result in severely oiled seabed sediments, where they may persist for years and potentially have long-term effects. A notable example occurred in two estuaries on the north-west coast of France following the 1978 *Amoco Cadiz* oil spill (see page 25). Fortunately, such conditions are unusual and most dispersed oil is more widely distributed and biodegraded before it can become incorporated into seabed sediments. However, the presence of loose flocs of oiled particles (i.e. flocculent material formed by aggregation of suspended oil and sediment particles) can result in filter-feeding animals on the seabed being exposed to elevated concentrations of hydrocarbons.

Sinking

Sinking is often discussed along with sedimentation (described above), but from an ecological perspective it is very different because it does not produce plumes or flocs of oiled particles. Sinking occurs if the spilled oil is denser than seawater, and can result in very persistent accumulations that lie on the seabed and sometimes become buried. The impacted area of seabed is typically smaller than that affected by sedimentation of dispersed oil, but sunken oil can cause long-term smothering and loss of habitat. Not many oils are this dense, even after much weathering. However, a few very dense oils, including Group 5 oils (see Box 1) and some others that can weather to a high density, can

On some shores in Louisiana, during the Macondo well incident that took place in the Gulf of Mexico in 2010, oil became mixed with sand in the surf zone, thereby sinking and forming oil mats in the shallow subtidal and lower intertidal zones.

sink in some circumstances. For example, wind-blown sand can sometimes be deposited on floating oil causing it to sink, and layers of fresh water on the sea surface near rivers or ice floes can reduce the density of the seawater, again allowing the oil to sink. Burnt residues of oil can be heavier than seawater and therefore prone to sinking. While such circumstances are not commonplace, spilled oil often comes ashore on sand beaches and mixes with sand in the surf zone, resulting in the formation of tar balls and tar mats that can sink in the shallow subtidal zone just off the beach. Again, these may be persistent and provide a potential long-term (chronic) source of contamination, though the toxicity of the oil is largely trapped inside the tar matrix so it has very limited bioavailability.

Shoreline stranding

The processes described above progressively reduce the quantity of oil in a surface slick, so it is possible for an offshore oil spill to result in no oil, or only small amounts of oil, reaching the shore. However, most moderate or large spills result in at least some shoreline oiling, which may then impact the full range of habitats and species present below the high tide level, and sometimes above it.

Natural physical and chemical processes will continue to weather the oil and gradually remove it, but the speed of removal varies greatly and depends on a range of factors. Persistence will be greater in places that are sheltered from wave action and water movement, but only small amounts of wave action are required to remove oil. Residues that remain for more than a year or two are generally only found in very sheltered situations or in locations where it has been deeply buried. For more information on the fate of shoreline oil see the IPIECA-IOGP Good Practice Guide on the impacts of oil spills on shorelines (IPIECA-IOGP, 2015a).

In some situations natural processes can remove shoreline oil very quickly. The photograph above shows a wave-exposed shore in Milford Haven, Wales, where crude oil from the 1996 Sea Empress *spill smothered sand and rocks to a thickness of many centimetres in places. Within two months (above right), most of the oil had been removed by wave action and manual clean-up; within a year no visible oil remained. In other situations (right) shoreline oil may persist for many years, as shown by this thick tarry residue from a spill in the Arabian Gulf.*

Photo-oxidation

Hydrocarbons exposed to ultraviolet (UV) light can be photochemically oxidized to form other compounds. This is often a minor component of the weathering process but PAHs are particularly sensitive. Laboratory studies of some compounds have found that the resulting products can be more toxic than the parent compounds, largely because they are more soluble in water. This increased bioavailability also increases their potential for biodegradation. The extent to which UV light has any effect on whole oils and on overall toxicity in the natural environment is the subject of ongoing investigations.

Biodegradation

Marine bacteria have evolved to produce enzymes that allow them to utilize hydrocarbons from crude oil as a food source. By metabolizing hydrocarbons they grow and multiply, and in turn become a food source for other organisms. It is through this natural process that the majority of the oil from a spill is ultimately biodegraded, and the energy and materials contained within it are returned to the food chain. Degradation requires adequate oxygen, nutrients and trace elements and its rate is primarily dependent on the ratio of surface area to volume of the oil, i.e. finely dispersed droplets will degrade rapidly while a thick slick or a patch of oil on a shoreline will degrade slowly. Large hydrocarbon molecules are not readily biodegraded and can persist for many years; these include some PAHs that are potentially toxic but have extremely low solubility in water and therefore have very limited biological availability. Some of the largest hydrocarbons, such as asphaltenes (used for road asphalt), are so resistant to biodegradation that a patch of tar could remain for hundreds of years but is effectively inert. Bacteria that can degrade oil are present everywhere, though not always in large densities, so there can be a time lag before they have multiplied enough that their activity becomes appreciable. Biodegradation rates can be limited by the concentrations of available nutrients that the microbes require to multiply and grow. Lack of oxygen can also be a limiting factor in some situations, particularly within muddy sediments. Cold temperatures reduce the rate of biodegradation, but not necessarily to a great extent. Recent studies of deep water situations in the Gulf of Mexico show that the bacteria are adapted to the stable 5°C conditions and can degrade oil quickly if it is adequately dispersed.

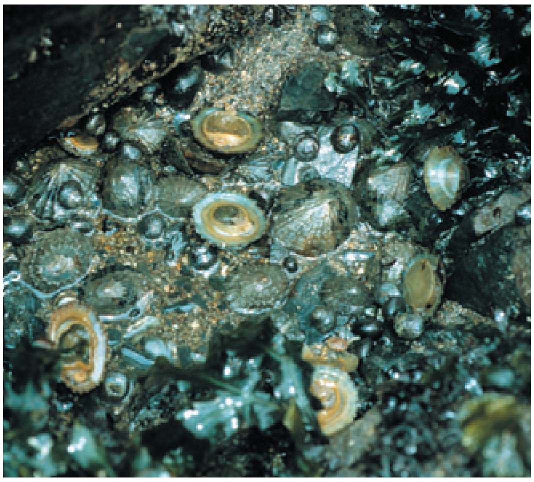
Ecological impacts and recovery

Exposure to oil and mechanisms of effect

As described in the previous section, spilled oil may be distributed into a number of different habitats and in different forms. In some rare severe situations, persistent heavy deposits on areas of shoreline or seabed can result in long-term loss of natural habitat, but there are many other possible effects of oil exposure. Depending on where and how an organism lives, it may be exposed to the oil in a variety of ways and the mechanism of any effect can also vary. For animals and plants that live or spend time on the surface of the sea or shoreline the greatest impacts are likely to be due to physical smothering, but they may also be exposed and impacted in other ways. For example: air-breathing animals may inhale volatile hydrocarbons or ingest oil with their food or when preening; some animals and plants may absorb hydrocarbons through their skin or other surfaces; and many animals have sensitive mucous membranes that will react to direct oil exposure. In the water column, dissolved hydrocarbons may be absorbed through gills or other exposed tissues, while dispersed droplets of oil may be captured and swallowed by filter feeding animals. Animals and plants that live on the surface of the shallow seabed (epibiota) may also be exposed to dissolved and dispersed oil, but if oil becomes incorporated into the sediment it will become available to a much wider range of sediment-dwelling animals.

The effects of physical smothering on organisms can include reduced ability to feed, move, respire or reproduce, or a loss of thermal control. If hydrocarbons are inhaled, ingested, absorbed or otherwise come into contact with an organism's internal tissues they can have a number of other effects. The chemical toxicity of the hydrocarbons can lead to damage and disruption of cell walls and cellular functions at the molecular level. If the dose (amount or concentration) and duration of exposure to toxic hydrocarbons is high enough the organism may die; if not it may exhibit some sublethal effects or remain unharmed. A common effect in many marine invertebrates exposed to oil is to be temporarily narcotized so that they stop feeding and don't react normally to stimuli. This can result in death if the animal becomes detached from its native habitat or is eaten by predators. Sublethal effects of oil spills that have been studied in some animals include effects on growth rate, reproductive capacity (e.g. sperm motility, egg hatching success), physiological activity (e.g. feeding rates and reaction to stimuli), tissue damage (e.g. skin ulcers, larval deformities) and genetic damage (e.g. altered forms of DNA).

In recent years, ecotoxicology studies of cells and biochemical systems in animals and plants have also identified a number of indicators of sublethal effects, collectively termed *biomarkers*, which may indicate exposure of the animal to particular contaminants, including PAHs. Examples include: the level of activity of cellular enzyme systems that protect cells by degrading potentially harmful chemicals (a widely studied indicator); the presence of breakdown products of PAHs in bile; and the level of stability of certain cellular organelles that are also involved in



These limpets were narcotized by acutely toxic oil from the 1996 Sea Empress *spill in Milford Haven, Wales. Their greatly reduced population had a knock-on effect on the whole rocky shore community. For more information on the impacts of oil spills on shorelines see IPIECA-IOGP, 2015a.*

detoxification. By indicating exposure, these biomarkers can be used in general environmental monitoring as early warning systems of potential environmental injury. In oil spill studies, these methods can provide complementary evidence to other ecological and ecotoxicology studies to describe the extent and magnitude of effects. However, it must be appreciated that other conditions can induce these biomarkers, so that biomarker levels alone are not reliable evidence of exposure to oil. Furthermore, evidence of exposure does not necessarily indicate injury.

Much of our understanding of toxicological effects (lethal and sublethal) now comes from laboratory based studies where animals and plants can be kept in controlled conditions with different oil types and concentrations. While such studies have been valuable it is important to appreciate that it is almost impossible to adequately mimic realistic field conditions, including habitat, ecological processes and the continuous dilution of oil over time. Validating the true scale of toxicological effects in the field is therefore difficult, and interpreting their ecological significance is even more difficult. A number of computer models have been developed, using a range of field and laboratory data, to describe the magnitude and geographic scale of toxicological effects in the marine environment. Validated results sometimes match those of empirical data, but considerable caution and an understanding of the limitations of the model is needed when drawing conclusions.

The extent to which an animal, plant or habitat will be affected by physical smothering will depend on the amount of oil that covers it, as well as on other factors described below. Similarly, the dose and duration of exposure to hydrocarbons are critical factors affecting the level of toxic effects that the hydrocarbons may have on an organism. Concentrations of dispersed oil just below a surface slick in open water can rise to levels that might be highly toxic if they persisted, but the duration is typically short as the slick moves on and the dispersed oil is diluted. Concentrations of oil in the sediments of an oiled shoreline may remain high in some patches of sediment for much longer. Concentrations of oil in an upper shore rock pool with a persistent patch of tar may be low, but the chronic inputs may persist for many years. Each situation can have different effects on individual organisms and, depending on the scale and distribution of the contamination, all of the individual effects may or may not add up to a population-level effect or loss of ecosystem services. Such impacts are also a function of population characteristics, behaviour and connectivity. All of these factors determine the population's resilience. For further information on this topic see IPIECA-IOGP, 2015a.

In addition to the direct effects of oil described above there are many potential indirect effects. If an oil spill results in a reduced population of a particular species it is possible that this will have consequences for populations of other species in the same food chain, above or below. Similarly, the physical space vacated by an impacted species may be taken over by another opportunistic species, and any corpses provide a short-term food source for others. The complex ecological interactions within communities can lead to many such possible effects (see the section on *Impacts on marine life and associated wildlife* on pages 20–38 for examples). It is also possible that indirect effects of oil spills could have impacts at the wider ecosystems level, though that possibility is still being evaluated.

Factors that influence oil impacts

It is clear that the impacts of an oil spill depend hugely on the circumstances. Spill volume is only one factor and not necessarily the most important. Oil source and type, wave action, water depth, the amount of sediment in the water, winds and tides, temperature and how close the spill is to the shore can make the difference between no detectable impact and a severe impact on many resources. The combination of these physical and chemical factors will also determine which habitats are exposed to the oil and in what form, e.g. a slick of oil on the water surface, a cloud of oil droplets in the top few metres of the water column, a floc of oiled particles on the seabed, a plume of oil rising from a subsea release, a coating of oil on a shoreline.

It is a feature of the marine environment that many species tend to aggregate at physical interfaces, between land and sea (coastlines), air and water (sea's surface) or where ice meets water. Oil also tends to concentrate at these interfaces. If the oil reaches the shore, other environmental factors including wave action, slope, substratum type and the presence of features that trap oil will also be important. Their influence on the persistence of oil on the shore will be one of the most important considerations for long-term impacts. These are described in greater detail in IPIECA-IOGP, 2015a.

In addition to those environmental factors, many ecological and biological factors also influence sensitivity, resilience and recoverability of individual species. Many of these can have consequent effects on communities and ecosystems. Examples are provided in the section on *Impacts of oil spills on marine life and associated wildlife* on pages 20–38.

Seasonality

Most species go through seasonal stages in their behaviour or biology (e.g. migrating, breeding, and spawning), particularly in temperate and polar regions. These different stages can greatly affect how vulnerable they are to an oil spill. Seasonality often results in a particular species or life stage being present or concentrated in a particular area or habitat at a particular time of year. As eggs and juveniles tend to be more sensitive than adults (partly because they have a larger surface to volume ratio), seasonal concentrations may be vulnerable to spills.

Below: little auk, like most Arctic birds, are highly seasonal in their biology and behaviour. They migrate north to the high Arctic in the spring to breed in large colonies and feed on small sea-ice crustaceans. In the winter they migrate south to the north Atlantic.

©Michael Haferkamp, 2002 https://commons.wikimedia.org/wiki/File:AlleAlle_2.jpg

Ecological function of key species

As mentioned in the *Introduction*, some species play a major role in the ecology of their communities. Some species (e.g. mangroves, marsh plants and corals) create a habitat that many other species depend upon. Other species can have a key role as predators, herbivores, scavengers and bioturbators (turning over seabed sediments). A relatively small effect on one of these species (sometimes called the keystone species) could have a consequent effect on the rest of the community.

Lifestyle factors

There are a number of biological traits that can make a species more or less able to recover quickly from an oil spill. These include longevity (lifespan), reproductive strategy and capacity (particularly numbers of offspring), mobility/dispersal potential (e.g. planktonic juveniles), growth rate, feeding method and geographic distribution. Thus, if a spill impacts a population of a species that is long-lived, slow growing with very few offspring per year and restricted to a small area, recovery from even a modest impact may be slow. On the other hand, a population of a species with the opposite traits is likely to recover quickly, even if large numbers are killed by the oil. Such species are said to be resilient. Some species with such traits may be opportunists, taking advantage of the stressed conditions that disadvantage less-resilient species, and may colonize quickly and dominate the habitat. Indeed, the notable increase in such species is a common indication that an impact has occurred. As the contamination reduces and the impacted species recolonize, the community will gradually recover its natural balance, sometimes through a series of successional stages. Examples of opportunists (discussed further in the next section) include ephemeral green algae on rocky shores and some species of polychaete worms in sediment communities.

Health and condition

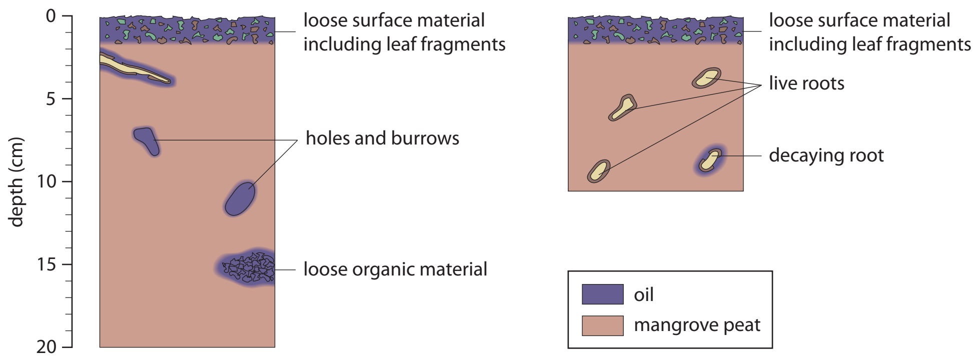
Individual organisms, populations and even communities and ecosystems that are already stressed from another cause may be impacted particularly severely by an oil spill. This is the concept of 'cumulative impact'. Migrating seabirds, for example, will be more sensitive to the effects of oiling if they have not recovered from severe weather during their journey. Multiple oil spills in the same location may also progressively reduce the condition and resilience of communities and the ecosystem, resulting in longer-term impacts.

In addition to the above, some species are simply more resistant to impacts from oil contamination than others, as a function of their anatomy, physiology, behaviour and other aspects of their individual complex biology. See the section on pages 20–38 for examples.

Long-term impacts and recovery

Notwithstanding the impacts of multiple spills in the same location (noted under *Health and condition*, above), the majority of oil spills are small releases of limited consequence. Further, for the majority of significant oil spills, the ecological impacts are limited in magnitude and duration, with few detectable effects lasting more than one or two years. Even in the case of large spills most marine habitats and populations that have been exposed to oil recover rapidly, and any longer-term impacts are typically confined to relatively small areas. Where longer-term impacts have been described, the primary cause is persistent oil, usually in the form of heavy residues or incorporated into muddy sediments, and most often in habitats that are sheltered from water movement. Where oil is not persistent, i.e. in most other areas affected by the spill, recovery is typically rapid and only limited by the speed of natural processes. Other causes of potential long-term effects include over-intrusive response (e.g. physical damage to habitat by clean-up activities), significant mortality of a long-lived species (i.e. species that take time to reproduce and return to pre-spill population levels) and other factors that result in slow recruitment of the impacted population (e.g. populations that are geographically isolated). Examples of each of these are provided in the following section.

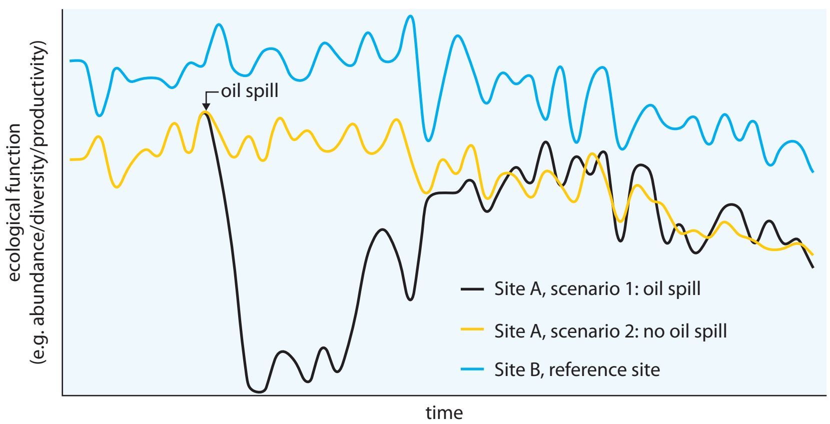
Figure 3 *Two core samples taken from a mangrove swamp following a refinery spill in Panama in 1986*



Oil from a refinery spill in Panama impacted mangroves and penetrated sediments. This persistent contamination became a source of chronic oiling that impacted a neighbouring coral reef for some years afterwards.

Whatever the magnitude or scale of impact, natural recovery will eventually take place, although there is continuing debate about how long the process takes in many situations. Recognizing the early stages of recovery is usually straightforward, but the latter stages are often difficult to describe precisely. In most instances it is difficult to establish when recovery is complete and scientists are typically conservative in their analysis. A significant challenge is that there is no widely accepted definition of *recovery* or *recovered*. Traditionally, and to a large extent still today, populations and communities have been described in terms of the abundance and/or biomass of each recognizable species. Logic therefore suggests that *recovery* can be described simply as the return to pre-existing abundances or biomass levels for each species. However, it is recognized that biological resources and many environmental factors that characterize biological habitats are in a continuous and largely unpredictable state of flux. For this reason, a damaged resource cannot necessarily be expected to go back to exactly what it was before the spill; equally, it is not possible to predict exactly what the resource in question would have been like if it had not been damaged by the spill. Current definitions of recovery often refer to the ecological function and/or ecosystem function provided by the species/population/community to the wider environment. Two such functions that are widely recognized as being important for communities and ecosystems are biodiversity (the variety of life) and productivity (the amount of biological matter created per unit time).

Figure 4 *Example of natural fluctuations in ecological function at two neighbouring sites and the potential impacts of an oil spill, with subsequent recovery, on one of them*



Sites A and B have different environmental characteristics, so measurements of ecological function cannot be directly compared at any particular point in time; however, overall trends in function are similar, allowing some assessment of recovery.

Impacts of oil spills on marine life and associated wildlife

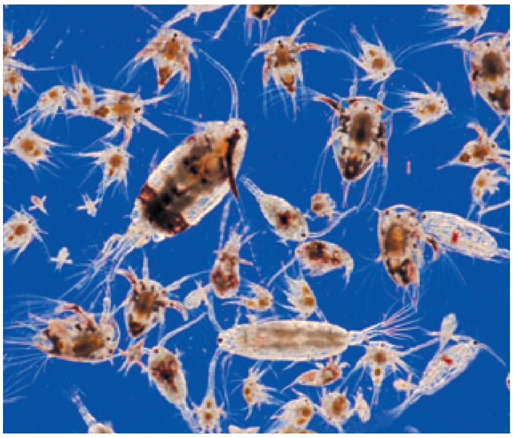
Plankton

Plankton includes microbes (bacteria, etc.), phytoplankton (small, often single-celled algae) and zooplankton (mostly small crustacea, but also jellyfish and other animals), plus the spores, eggs and larvae of other plants and animals (algae, invertebrates and fish). Densities of plankton are greatest in coastal waters where nutrient concentrations are sufficiently high to sustain them and close to the populations of adults. This large diffuse biomass is at the base of most marine food chains.

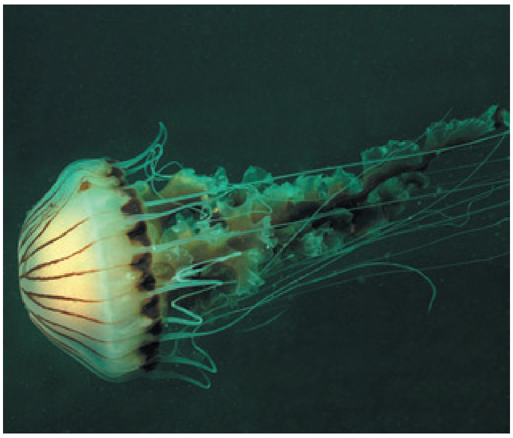
Planktonic organisms are relatively sensitive to toxic effects from hydrocarbon exposure, particularly water soluble fractions and small oil droplets, and laboratory studies have described a wide range of acute, chronic and sublethal effects on various species and life stages. However, most studies of natural plankton communities in the sea have found a rapid return to normal densities and community composition once the oil in water concentrations have returned to background levels. Their ability to recover so quickly is due to short generation times, the production of large numbers of eggs and juveniles, distribution over large areas and rapid water exchange. Few studies have described effects on densities of planktonic species lasting more than a few days or weeks. For example, studies following the grounding of the Soviet tanker *Tsesis* in 1977, during which 1,000 tonnes of medium grade fuel oil were released into the Baltic Sea, showed that zooplankton biomass declined substantially close to the wreck during the first few days after the spill but was re-established within five days. Oil contamination of zooplankton was recorded for more than three weeks and it was suggested that a short-term increase in phytoplankton biomass and primary production in the impacted area was due to decreased zooplankton grazing rates.

Potential concerns for certain vulnerable species and life stages remain. Some species of fish have genetically isolated populations that spawn in particular locations and have planktonic eggs or larvae that may be vulnerable. If a large spill occurred in the same area and at the same time as the spawning or post-spawning development, it is possible that there may be significant mortality among eggs or larvae. Given the large numbers of eggs produced by most fish and the small proportion that need to survive to maintain the adult stocks, it is still unlikely that a spill would have a detectable impact on the fish population. A recent example of such concern involves

Plankton vary in size. Those near the surface are vulnerable and sensitive to elevated concentrations of hydrocarbons under an oil slick. However, during most open water spills, the exposure of plankton is short-term and recovery is rapid.



Wellcome Images



western Atlantic bluefin tuna in the Gulf of Mexico; these are known to spawn in an area that partially overlaps with the area of sea affected by oil released from the Macondo well blowout in 2010, and lay eggs that float at the surface. Laboratory studies in Australia have shown that hydrocarbons can affect the development of Southern bluefin tuna embryos, providing a possible mechanism for effects. However, the published results of field studies investigating Atlantic Bluefin tuna in the Gulf of Mexico present no evidence of effects.

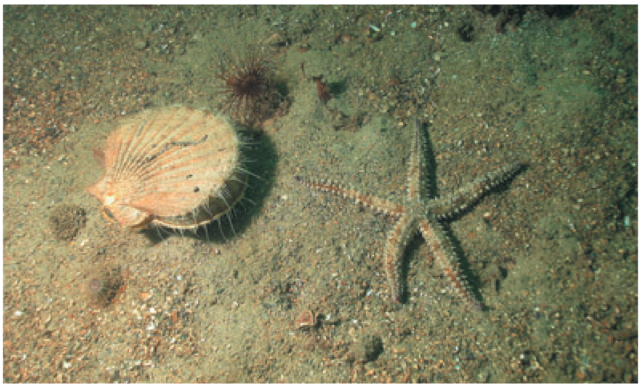
Seabed life

Sediments, with varied mixtures of mud, sand and gravel, comprise the majority of seabed habitats in offshore areas, while bedrock and boulders are more common near the coast. The diversity of habitats is as great as that found on land. Some habitats are dominated by, or even formed by, certain species or groups of species, e.g. kelp forests, seagrass beds, mussel beds and coral reefs. Algae and seagrass beds are only found in relatively shallow water where there is sufficient light (i.e. at a maximum of a few tens of metres), but animal communities are widespread at all depths.

The vulnerability of seabed communities to oil from surface spills is dependent primarily on water depth, as ecologically-significant concentrations of dissolved or dispersed oil from surface slicks rarely reach below 10 metres. Furthermore, it is unusual for high concentrations to remain over a particular patch of seabed for long. As a slick moves on and becomes weathered over time, the potential for concentrations of hydrocarbons that may have toxic effects reaching even shallow seabed areas decreases further. For example, during the 1991 Gulf War, oil released in the north of the Arabian Gulf moved south into Saudi Arabian waters and passed directly over shallow coral reefs with no detectable effects.

Subsea blowouts may have higher potential for seabed impacts in deep water, depending on circumstances. During the Macondo well oil spill in the Gulf of Mexico chemical dispersants were applied at the well head to enhance dispersion and increase biodegradation of the oil. Studies have shown that deep water currents carried dispersed oil droplets above the seabed for many kilometres. However, the oil concentrations were low; extensive monitoring of the subsea plume found levels of volatile hydrocarbons at a maximum of 1.2 ppm (parts per million) just over 1 km

Kelp forests and seagrass beds also grow in shallow waters and are characterized by high biodiversity and productivity. The plants are not particularly sensitive to elevated concentrations of hydrocarbons, but many of the animals that live in these habitats are, including juvenile fish.



Seabed habitats at depths below 10–20 metres have little or no vulnerability to dispersed oil from surface spills.

from the well head, and levels of <0.1 ppm at distances greater than 20 km. The equivalent figures for semi-volatiles (organic compounds that can evaporate at ambient temperatures but only slowly) were <0.5 ppm maximum and <0.01 ppm at distances greater than 10 km. Fish and seabed communities may therefore have been exposed to elevated concentrations but there is little evidence that the dispersed oil contaminated seabed sediments. Laboratory studies and empirical evidence indicate that if dispersants had not been used, more of the oil would have risen to the surface and exposure to the seabed may have been reduced, but impacts on surface and shoreline resources would have been greater. A net environmental benefit analysis (see the section entitled *Managing oil spill response and potential impact* on pages 39–43) concluded that the trade-off was appropriate, although this is not a universally accepted view. Other circumstances that could result in deep water seabed contamination include spills of high density oil that weather and sink, as described on pages 12–13.

A high diversity of marine life is also found in the deep sea. It is not vulnerable to surface spills, but there is potential for hydrocarbon exposure from sub-surface spills.

In the unlikely event that elevated concentrations of oil in water do reach the seabed, any organisms that are directly exposed to the water column will be vulnerable, including plants and animals that live on the surface of the seabed, known collectively as the *epibiota*, and any burrowing animals that actively pull water into their burrows or tissues for feeding or irrigation. Most other animals that live in the sediment will be partially protected unless oil becomes significantly incorporated into the sediment, which only happens in certain circumstances (see *Sedimentation* on page 12).


NOAA/MBARI

Shallow water seabed epibiota may be vulnerable to concentrations of oil close to the bottom, but many will be relatively insensitive to even high concentrations because the duration of exposure is typically short. The effects of oil on macroalgae, such as kelp and many other species which dominate hard substrata in shallow waters is small due to their mucilaginous coating that resists oil absorption. Many sessile invertebrates, even some that feed by filtering or capturing particles from the water column and therefore take up oil droplets readily, like sponges and sea-squirts, will also survive apparently unaffected by high concentrations. It may be that these animals are temporarily affected by a short high dose of hydrocarbons (as mentioned in the section on *Ecological impacts and recovery*, on pages 15–19) but not killed. Mussels are another example: they readily pick up oil from the water column and accumulate it in their tissues, but are resistant to its toxic effects. A number of sublethal effects on their growth, reproduction and other tissue effects have been described, but once the oil has gone and their tissues have cleared (a process termed depuration, which can take months) they normally survive well, with no detectable effects on their populations.

However, some groups of seabed animals are sensitive to even brief exposures of relatively low hydrocarbon concentrations in water, including burrowing bivalves and small crustaceans called amphipods.

Some filter feeding bivalves that live in nearshore sediments will react to a dose of oil in water by ejecting themselves from the sediment. After some coastal spills, large numbers of affected bivalves, e.g. razor clams and cockles, have been washed up onto the shore and then concentrated along the strandline. Some bivalves can live for many years or decades, and if a notable proportion of their population has been lost, it may take some time to recover. Other sediment-based animals that pull water into their burrows and have been found washed up on beaches after oil spills include heart urchins and masked crabs.

Large numbers of cockles, clams and some other burrowing animals ejected themselves from shallow subtidal sediments after exposure to elevated concentrations of oil in water during the 1996 Sea Empress *oil spill. Some were then stranded on nearby beaches.*

Some amphipods (of which there are large numbers of species, adapted for a large variety of habitats) are also filter feeders, and many studies have reported spill-related impacts on their populations. Some amphipods are often used as test organisms in sediment toxicity studies as they have been found to be good indicators of contamination. Shallow water amphipods in temperate and tropical zones typically have short lifespans and multiple generations per year, so recovery of their populations is normally rapid. However, during the 1978 *Amoco Cadiz* oil spill there was a relatively localized dramatic fall in the previously high densities of a tube-dwelling amphipod (*Ampelisca*), and a consequent change in the rest of the community. It took 15 years for the high amphipod densities to return, and for a community structure similar to that present before the spill to be re-established.

Impacts on nearshore populations of amphipods and burrowing bivalves have been reported following many coastal spills, but often there have been few other detectable effects on seabed communities. To some extent this may be due to the logistical difficulties of sampling and maintaining pre-spill data for comparison, but this was not the case with the 1996 *Sea Empress* spill in south-west Wales, UK, where a number of monitoring programmes had been ongoing for many years. Approximately half of the 72,000 tonnes of crude oil spilled was naturally and chemically dispersed, and seabed studies showed marked reductions in densities of small crustaceans

Large numbers of shallow-water dwelling marine life were killed by naturally dispersed home heating oil from the 1996 North Cape spill.

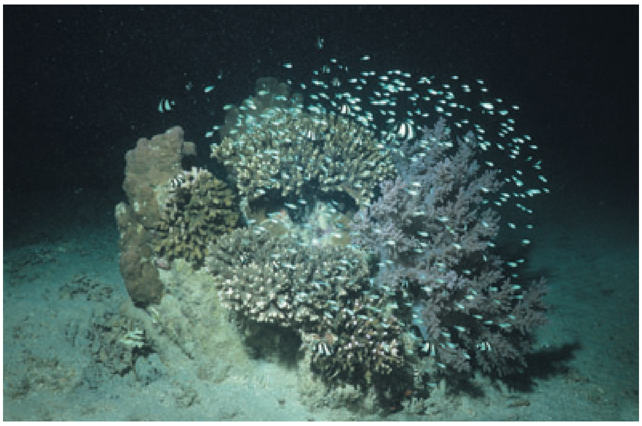
(amphipods and cumaceans) in the vicinity of the wreck, but no other notable effects on seabed communities. Monitoring studies showed a clear pattern of recovery of amphipods over a period of five years, with densities similar to pre-spill levels by 2000. Large numbers of bivalves and heart urchins were washed up on some beaches, but post-spill studies found large populations remaining. There was no evidence of persistent contamination from the crude oil, but recent forensic studies of seabed sediments in Milford Haven have found detectable concentrations of the heavy fuel oil that was also spilled from the tanker. To date there have been no studies to assess whether these concentrations have any chronic toxicity.

Dr Erich Gundlach, E-Tech

Notable impacts of oil-in-water concentrations on other seabed organisms have occurred in some spills, where the combination of dose and duration has been enough to cause mortalities. One example took place in 1996 when the tank barge *North Cape* struck ground off the coast of Rhode Island, USA, releasing approximately 3,100 cubic metres of home heating oil, a relatively light product. Large numbers of juvenile lobsters, clams and other species were killed by exposure to high concentrations of naturally dispersed oil. The majority of the impacts occurred in nearshore areas no more than a few metres deep. Adult lobsters were not significantly affected as they were migrating to deeper water for the winter when the spill occurred; it was therefore expected that the supply of lobster larvae for recovery of the population would also be unaffected. Nevertheless, with nearly three million juvenile lobsters washed ashore, nearly one-fifth being over two and up to seven years old, the recovery was estimated to take several years. A restocking programme was carried out but studies showed that recovery did not occur as well as expected due to heavy fishery exploitation and other impacts. Recovery of the clams was also expected to take a number of years and a restoration programme for various species was carried out.

Tropical coral reefs can form extensive areas of high biodiversity in shallow water, where they may be both vulnerable and sensitive to oil spills.

Tropical coral reefs have also been impacted by oil spills, and the longest-term effects have occurred where there was mortality of the corals themselves. However, sensitivity varies between coral species and, again, most appear not to be acutely sensitive to short-term elevations in oil concentrations. Reefs deeper than 10 metres are unlikely to receive oil exposures from a surface spill that cause significant impacts. Sometimes other invertebrates living in the reef are impacted



more than the coral, and sometimes there are no recorded impacts. One of the best-studied tropical spills occurred at a refinery in Panama in 1986, where 38,000 tonnes of medium crude oil released from a ruptured storage tank impacted intertidal and shallow water coral reefs. This caused substantial damage to the corals, to water depths of around six metres, and recovery was slow due to chronic inputs of oil from severely oiled sediments in a nearby mangrove.

In the 1984 TROPICS study, a large-scale field experiment was carried out to compare the effects of chemically dispersed oil with those of undispersed oil. The results showed short-term (one year) declines in coral cover and in other coral invertebrates and territorial fish at the dispersed oil site. There were also lesser reductions in coral cover over the short term at the undispersed oil site, but the cover then increased at both sites. This is in contrast to the much more obvious and long-term impacts on mangroves at the undispersed oil site.

In situations where significant amounts of oil become incorporated into muddy sediments, or where a sinking oil residue forms a layer on the seabed, it may persist for years as biodegradation can be slow due to lack of oxygen. The oil toxicity can affect the sediment community, and a layer of sunken oil may also act as a barrier to colonization. In time, the toxicity will reduce as the oil weathers, though some toxicity may remain trapped under the surface. The case of the 1978 *Amoco Cadiz* oil spill is the most severe example recorded. Concentrations of oil in the clay sediments of two estuaries reached high levels and opportunistic polychaete worms became dominant for a few years until the sediment toxicity had reduced. The oil was also shown to cause tissue damage and to have other sublethal effects in a species of flatfish, which were still evident eight years later. Other examples, with lower sediment concentrations and less severe impacts, include shallow water seagrass beds affected by the 1989 *Exxon Valdez* spill, and relatively deeper (30 metre) sediments impacted by the 1977 *Tsesis* spill in the Baltic Sea. Examples of sunken oil impacts include the 1991 *Haven* spill off Genoa, Italy, where large quantities of burnt residue from explosions and fire on the vessel settled to the seabed and formed a hard layer which was then partially colonized by epibiota. Studies also found some evidence of sublethal toxic effects in tissues of flatfish sampled from the area. This is not, however, a representative example of the impact of residue remaining after controlled in-situ burning of spilled oil, where floating oil is contained and burned over a much wider area resulting in low concentrations of scattered residue that may reach bottom sediments.

Seabed communities in polar seas have some notable differences from those in warmer seas, as a higher proportion of species are long-lived and slow growing. The lack of case studies means that it is difficult to make confident predictions about the impacts of oil reaching those habitats, but studies of seabed sediment communities during the Baffin Island Oil Spill experiment (see page 42) found very limited effects of either dispersed or undispersed oil, with no detectable effects beyond two years at the worst-affected site. Some authors suggest that seabed communities in polar seas may be no more sensitive to oil than those in temperate climates; however, if there was an impact, recovery may be prolonged by the slower ecological processes. A study of the 1987 *Nella Dan* diesel oil spill in the Australian sector of the Antarctic indicated that this incident led to high mortalities in invertebrate communities of intertidal and shallow subtidal rock habitats. The intertidal communities recovered quickly, but communities of animals living within kelp holdfasts showed some longer-term effects. Seven years after the spill, the holdfast community structure in samples from heavily oiled sites showed moderate levels of recovery, including populations of sensitive species.

Similarly, seabed communities in the deep sea are also characterized by long-lived species, and may take a long time to recover from the impacts of a spill. Studies in the Gulf of Mexico following the 2010 Macondo well incident identified areas of sediment contamination in the vicinity of the well head in the first year after the event, together with reduced diversity of sediment communities in those areas at that time and a small number of cold water corals in poor condition. However, the majority of cold water corals appear to be unaffected by the incident, and the evidence is currently too limited to make firm conclusions about the long-term effects of the spill or to draw general conclusions about the impacts of subsea releases on the seabed.

Fish and fish stocks

The emphasis of this section is on finfish, but some crustacean and molluscan shellfish that are regular components of capture fisheries are also discussed. Most crustacea and molluscs are important in seabed communities, and are discussed above. Relatively few species of fish contribute to commercial fishery catches but they all play a part in one or more ecosystem food chains. Most, but not all, can be placed in one of three ecological groupings—pelagic, demersal or benthic:

- *Pelagic* fish, which include anchovies, herring, tuna and squid, live in open water, typically feeding on plankton and other small fish, and tend to be very mobile. Many are migratory, moving to different areas for different seasons or different parts of their life cycle.
- *Demersal* fish, including cod, redfish, wrasse and many shark, spend most of their lives close to the seabed where they find most of their food, but may also move up into midwater. They are not as mobile as pelagic species, and while some are migratory most spend long periods in the same vicinity.
- *Benthic* fish, including all flatfish, catfish, gurnard and most shellfish, live on the seabed, rarely swimming up into the water. They are generally much less active than pelagic and demersal fish and many have strong behavioural ties to a particular location.

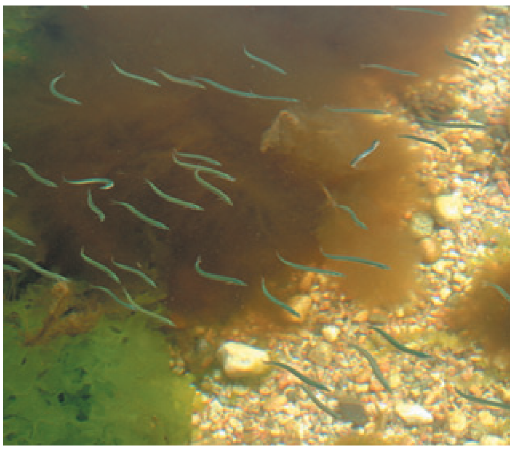
Other useful ecological groupings are the anadromous and catadromous fish, including salmon, sturgeon and eel, that migrate to fresh water or to the sea, respectively, to spawn. These groupings are relevant when considering vulnerability to different oil spill situations.

As described above for seabed life, the likelihood of fish or shellfish becoming exposed to water-soluble hydrocarbons or dispersed oil droplets from a surface oil spill depends greatly on the depth of water at which they live. It is for this reason that many countries typically only allow the spraying of chemical dispersants onto a surface slick in waters deeper than 10–20 metres without the need for a detailed study of specific marine resources. The logic behind this is that the increased dispersal of oil into deep water is unlikely to affect fish populations or other important resources in those areas; for example, benthic and demersal species will be below the depths that elevated concentrations of oil are likely to reach, while pelagic fish avoid surface waters to reduce risk of predation by birds, and are so mobile that they are unlikely to be exposed to high oil concentrations for long periods. Further, there is some evidence from studies of contaminated salmon runs and laboratory experiments that fish can detect (using sensitive taste receptors in the lateral line along their flanks), and will avoid, water contaminated with oil; however, there is also some evidence that other stimuli will override such avoidance patterns. Whatever the reasons, it is clear that the likelihood of fish mortality from open water oil spills is small, whether chemical dispersants are used or not; there are no published records of significant fish deaths in offshore areas and very few from open coastal areas.

As discussed in the section on seabed life (pages 21–26), subsea blowouts may result in deep sea fish becoming exposed to concentrations of hydrocarbons, but the potential for toxic effects is not known. Very little is known about the biology of deep sea fish and their response to hydrocarbon contamination. Monitoring during the 2010 Macondo deep sea release showed a diluting subsea plume around 300 m above the seabed, with oil concentrations dropping to around 1 ppm just over 1 km from the well head and <0.1 ppm at 20 km, albeit these levels were sustained while the release continued. Data on the effects of Arctic oil spills on fish is too limited to provide much information on relative vulnerability and recovery potential. Toxicological studies indicate that Arctic species require a longer period of time to exhibit effects associated with oil exposures but that their sensitivity is similar to temperate species.

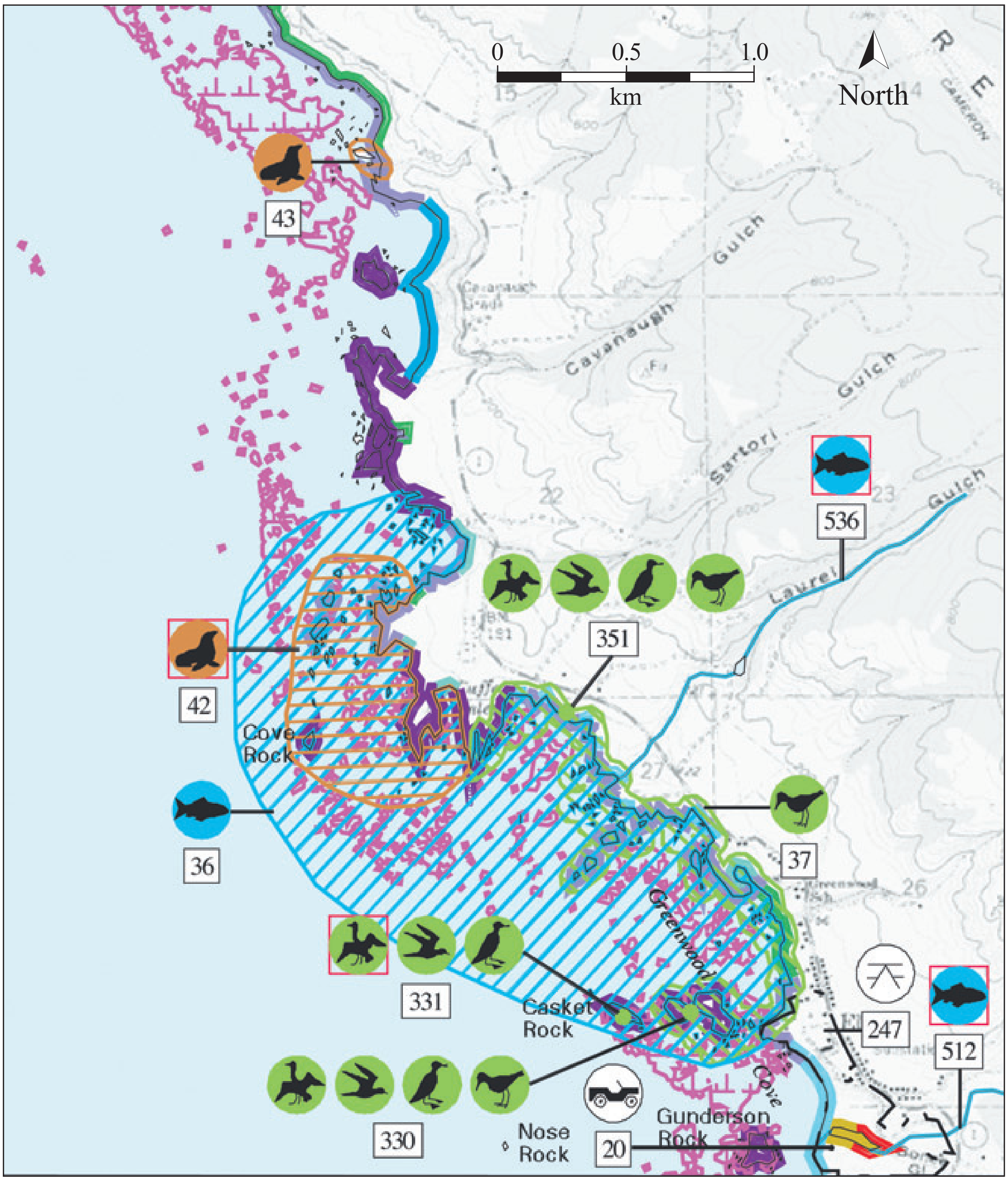
The risk of exposure increases if a spill occurs in shallow water and in any other situation where the rate of dilution of the oil concentrations may be limited, e.g. in lagoons, estuaries and embayments. Other factors, described in the section on the fate of oil (pages 9–14), will also affect the available concentrations of dissolved and dispersed oil. Many species of demersal and benthic fish are adapted to living in shallow water habitats, while many others move into shallow water to breed and/or spawn. Some species are territorial, particularly in the breeding season, and are unlikely to move away even if they could. Some migratory species will pass through shallow coastal habitats in large numbers at particular times of year, making them much more vulnerable to a spill if it happened to coincide. The juvenile stages of many fish, including many commercial species, are concentrated in shallow water habitats like seagrass beds, kelp forests and mangroves where food is abundant and they can hide from predators. These nursery areas are often highlighted on oil spill sensitivity maps to aid their protection by response decision makers. Laboratory-based toxicity tests have shown that eggs, larvae and juveniles of fish, like those of other animals, are generally much more sensitive to hydrocarbons than adults.

For most fish species, each life stage lives in a different habitat. Juvenile fish of many species spend their first months in shallow (<10 metres) vegetated habitats to avoid predators. These areas will be vulnerable to hydrocarbons in water from a surface spill.



A coastal spill that results in sustained high concentrations of hydrocarbons in nearshore waters therefore has a greater risk of toxic effects on fish populations. Such spills have occurred, for example the 1969 *Florida* barge spill in Buzzards Bay, Massachusetts, which took place in stormy weather, resulted in 570 tonnes of No. 2 home heating oil being mixed into shallow coastal waters, and a large kill of small (non-commercial) fish and seabed invertebrates. The 1978 *Amoco Cadiz* grounding in Brittany, France, spilled 221,000 tonnes of light crude into coastal waters and killed large numbers of wrasse and sand eels. Fish population studies reported that a whole year class of

Figure 5 *An environmental sensitivity map from northern California. The blue hatched area is a known nursery area for juvenile rockfish—for more details see the NOAA website on Environmental Sensitivity Index (ESI) Maps*



NOAA

juvenile plaice and sole (both flatfish) had been lost in at least one area, but there was no evidence of subsequent impacts on fishery stocks. The 1996 *North Cape* spill, described on page 24, also resulted in fish kills.

None of the above spills, or indeed any others described in the available literature, have resulted in substantiated impacts on commercial wild finfish stocks. This should not be surprising; even in a worst-case scenario of a large spill coinciding with a geographically isolated spawning event it would be extremely unlikely that a notable proportion of the adult stock would be exposed to a sustained lethal dose of hydrocarbons. While it is more likely for substantial numbers of eggs, larvae or juveniles to be killed, the reproductive strategy of fish allows for huge losses of young, and any reduction that happened to carry through to the numbers of young adults would be undetectable against the natural level of population fluctuations.

However, the fortunes of the Pacific herring in Alaska following the 1989 *Exxon Valdez* spill initially convinced some people that oil spills could have serious impacts on fisheries. Pacific herring lay their eggs on kelp in shallow coastal areas, and some of these spawning areas were exposed to oil from the *Exxon Valdex* spill. Four years later, when that year class would have been joining the adult stocks, the herring stock collapsed and the oil spill was considered by many to be the obvious cause. Many years of research later it was unequivocally shown that disease and poor nutrition of the herring population were the cause and that the oil spill almost certainly had no significant effect.

Impacts of oil spills on local populations of less mobile fish and shellfish have been described in rare cases; however, recovery is typically rapid unless recruitment is slow, the species is long-lived, or there is continued persistent oil contamination. For example, high concentrations of oil in water from the 1993 *Braer* spill resulted in a complete loss of small territorial inshore fish (rockling and eelpout) in the vicinity of the wreck site, but recolonization started after one year. Following the 1991 Gulf War oil spill, prawn stocks in Saudi Arabia fell dramatically to 25% of their pre-war levels, due to a spawning failure. The spill was considered to be the likely cause, but a mechanism for the failure was not determined, though there were many theories. The effect was localized, as the Kuwait fishery had relatively good years in 1992 and 1993. By contrast, in the Gulf of Mexico, following the 2010 Macondo well incident, studies in shallow inshore seagrass beds have found no effects of the oil on numbers of juveniles except for some indications that they may have benefited from the fishery closure. In this incident, the effectiveness of the subsea and offshore response is likely to have made a significant contribution to the protection of fish populations in the shallow inshore waters.

Mortality in ballan wrasse was due to exceedingly high concentrations of oil in water near the wreck during the 1993 Braer *spill.*

Sublethal effects of oil on finfish and shellfish have been described in laboratory experiments and in samples collected from areas impacted by oil spills. Experimentally-described effects include various impacts on reproduction (e.g. egg hatching, larval survival and larval development abnormalities), physiological functions (e.g. swimming and feeding rates), tissue damage (e.g. skin disease and blood cell counts), biomarker indicators of exposure and many others. However, it is worth noting that laboratory studies may not accurately mimic the oil concentrations and exposure durations typically found in the field, and that only a few of the effects mentioned here have been shown to occur in the field after real spills. Biochemical (biomarker) evidence of exposure to oil has been shown in many species after numerous spills, but evidence of significant injury to finfish has largely been limited to histopathology (tissue damage) in flatfish and other benthic species that have been chronically exposed to persistent oil residues. For example, recent studies of killifish in saltmarshes oiled by the 2010 Macondo well incident have been found to show some evidence of effects on tissue morphology, although another study found no difference in the species composition, abundance or size of saltmarsh fishes at oiled and unoiled sites in Louisiana two to three years after the spill.

Indirect impacts on fish populations through reduced availability of food is another consideration, particularly if the main prey (e.g. amphipods) of a fish or fish life stage is severely impacted by a spill. Such impacts have not been described or detected against the background of natural variation and would, therefore, be relatively minor if they are occurring.

From a fisheries perspective one of the greatest concerns of an oil spill is the potential for tainting, where hydrocarbons taken up by tissues of the fish or shellfish can be tasted or smelt. Tainting occurs at very low levels of hydrocarbon in the tissues. It leads to a highly unpleasant taste which effectively renders the fish inedible and thereby unfit for market. This may result in economic losses for a fishery but does not affect populations or ecological function. In finfish the hydrocarbons are typically metabolized within days or weeks and stocks return to being taint-free, with longer times typically shown in oily fish like salmon. In crustaceans and molluscs, which cannot readily metabolize hydrocarbons, the process is much slower and the taint may persist for months or even years.

Marine mammals

Marine mammals, including cetaceans (whales and dolphins), seals, manatees and otters, are difficult animals to study because of the understandable reluctance of researchers to capture them or in any way harm them in the process of collecting information. Empirical data on the effects of oil spills are therefore limited, and much is based on remote observation and analysis of corpses. However, for most marine mammals the number of recorded corpses reasonably attributed to impacts of oil spills has been small. Many of the most detailed studies on marine mammals were carried out in Alaska following the 1989 *Exxon Valdez* oil spill.

Exposure to liquid oil on the surface of the sea or shoreline is the primary risk, and the marine mammals that are most vulnerable, if an oil spill happens in the area where they live, are sea otters and, to a lesser extent, seals. Even small amounts of oil will rapidly soil otter fur and impair its properties for insulation and water repellence. As the animal tries to clean itself it can also ingest oil

The sensitivity of orca, dolphins and other cetaceans to oil spills appears to be small.

which may cause internal tissue damage. Following the *Exxon Valdez* spill, at least a thousand sea otters were seen oiled and 871 corpses were collected. Recovery of the population was complicated because, like all mammals, the regional population is made up of many local populations, each with their own social and population dynamics, and each subject to local environmental factors. Some local populations recovered within a few years, while others took longer or, in at least one area, declined further for reasons that are not clear and may be unrelated to the spill. Evidence from biomarker studies of continued exposure of otters to PAHs, up to nine years after the spill, was linked by some researchers to persistent oil residues in the intertidal zone, but those residues no longer have sufficient bioavailable toxicity to have any significant ecological effect. Otters have also been a source of concern in other spills, for example the 1993 *Braer* spill off the Shetland Islands, though documented impacts from that spill were relatively limited. European otter populations may be less vulnerable to marine spills as they are more reliant on fresh water.

Left: many otters live on the coast, and their fur will readily pick up any oil on the water or shore.

Seals, sea lions and other pinnipeds do not rely on long fur for insulation, although most seals have short fur that can become soiled by oil. Their bodies are therefore relatively insensitive to oil, particularly in the case of those species that spend most of their time in the water. All pinnipeds do, however, spend at least some time on the shore, often aggregated in well-established haulouts, where they would be more vulnerable to any oil that comes ashore. Severe oiling by a viscous oil could therefore overwhelm any individuals that are unlucky enough to be affected. Smothered corpses of small numbers of seals, particularly pups, have been reported from a few spills, but not enough to have any significant effect on populations. In some cases, autopsies have found that the animals were already dead from other causes before they became coated

Below: pinnipeds, like these New Zealand fur seals, haul out onto shorelines to rest between periods of feeding.

with oil. A more common sublethal effect of oil spills on pinnipeds comes through exposure of sensitive areas of skin (mucous membranes) to hydrocarbons at the water surface while oil is fresh. Observations of animals with inflamed and streaming eyes and noses have been reported following a number of spills, though the natural incidence of respiratory diseases can complicate interpretation. The 1997 *San Jorge* oil spill in Uruguay led to oiling of an important fur seal rookery, with attendant concerns about impacts and potential disturbance from aggressive shoreline clean-up techniques. Although the spill led to the deaths of around 5,000 pups, this mortality was in the range of natural and harvest mortality. The use of low-technology clean-up minimized the risk of further oil-animal contact and stampede (in which the adult seals can trample and kill pups) due to human presence (Mearns *et al.*, 1999).

The pups of some seal species spend many days or weeks onshore before they are ready to swim, and are potentially vulnerable to any oil that lands there.

Whales and dolphins have been observed in the vicinity of numerous oil spills, but evidence of impacts on individual animals is limited and mostly circumstantial. This does not mean that impacts have not occurred, but that if they have occurred they have been too subtle for detection. Potential pathways of exposure to oil are similar to those for pinnipeds, i.e. contact with the skin, contact with mucous membranes (eyes and blowhole), inhalation of hydrocarbons, smothering of feeding structures (in baleen whales), ingestion of oil during feeding and ingestion of contaminated prey. While one might imagine scenarios that could result in a significant impact via those exposure pathways, the probability that any such scenario could occur is low. Experiments have shown that the skin of cetaceans is insensitive to contact with oil and that the natural healing process of cuts in the skin is also unaffected. Experimental evidence also suggests that baleen structures might become clogged in a worst-case situation, but that they self-clean rapidly. The likelihood that a feeding cetacean (even some baleen whales) would ingest a sufficient quantity of oil to cause sublethal damage to its digestive system or to present a toxic body burden is low, and autopsies of cetaceans have not found evidence of oil in their intestines. Similarly, hydrocarbon content in prey is unlikely to be present in sufficient quantities to be toxic to a cetacean, and most would be metabolized quickly. Some PAHs can accumulate in tissues of whales before they are eventually metabolized, as in all vertebrates. Lastly, inhalation of hydrocarbon fumes and their contact with mucous membranes could occur close to the source and time of a surface spill when the oil is fresh and concentrations of volatile hydrocarbons are temporarily high, but the likelihood that a cetacean would receive a sufficient dose to result in a toxic impact is low.

The strongest evidence that oil spill-related mortality can occur in marine mammals was published following the 1989 *Exxon Valdez* spill. Researchers studying pods of orcas (killer whales) reported notable reductions (33% and 41%) in the numbers of two pods that had been observed in the vicinity of the spill. Continued monitoring found that the two pods did not follow the population increases shown by other Alaskan pods. However, other researchers have raised doubts about the likelihood of direct oil spill effects and have suggested that a combination of other causes, including shooting by fishermen, old age and other contaminant levels, are more likely. There has been no clear conclusion to this debate. More recently, research in Louisiana has indicated poor health in a population of dolphins that live in one of the bays impacted by oil from the 2010

Macondo well incident and have suggested that the spill was the causal factor. However, at the time of writing, the evidence for this is limited. Reviewers have highlighted a number of confounding factors, along with the absence of a convincing exposure pathway and mechanism by which oil from the spill could have caused the effects described.

Other mammals that would be potentially at risk from an oil spill include dugong, manatees and polar bears. Empirical data on their vulnerability, sensitivity or recovery potential are almost completely lacking, though the limited evidence that is available suggests some potential for concern. Dugong and manatees live in shallow water and are slow moving, so would be vulnerable and might have some sensitivity.

Disturbance caused by oil spill response activity, particularly boat traffic, could affect the behaviour of some sea mammals through noise presence, or could increase the potential for injury by boat strike, if it takes place close to sites where they feed or rest.

Marine reptiles

Turtles are potentially vulnerable to oil when they come into contact with it at the surface of the sea or on the shore. Outside of the nesting season adults and juveniles spend relatively little time at the surface, but because they breathe air they do need to surface at intervals. When they are at the surface they can become oiled and, in a worst-case situation, they might be smothered, but there is little evidence to suggest that their skin is sensitive. Turtles do not aggregate and are widely distributed, so impacts are unlikely to result in population-level effects. They are at greater risk during the nesting season when adult females come ashore, usually at night, and drag themselves to the top of a sand beach to lay their eggs. This is a strongly seasonal activity, potentially involving large numbers of females returning to the same beach at the same time. The

U.S. Fish and Wildlife Service

Newly hatched turtles will be vulnerable to any oil that lands on the beach as they emerge from their nests and crawl to the sea.

nests are buried deeply in the sand, so the eggs are largely protected from contamination by anything less than heavy oiling with fresh light oil, but the hatchlings will be much more vulnerable. Hatching and movement of the hatchlings across the shore is synchronized to reduce predation losses, but this will make them much more vulnerable to oil contamination if this event happens to coincide with a spill. The juveniles are much more sensitive to oil toxicity than the adults, spend more time at the surface of the sea and may swallow small tar balls. Reports of juvenile turtle deaths have been made after some oil spills, and autopsies of those individuals have often found oil and tar balls in their intestines. Effects on local population levels would be theoretically possible if there was a severe impact on a turtle nesting site in the nesting season, but no such effect has yet been reported.

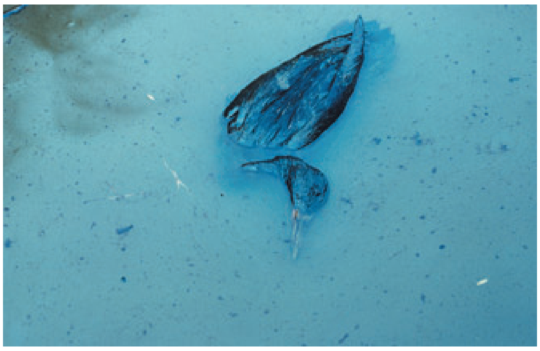
Around 450 live turtles, particularly Kemp's ridley turtles, with oil contamination were collected at sea during the 2010 Macondo well incident, though a greater number will have been impacted. The majority were taken to cleaning centres for rehabilitation and later released. At the time of writing it was not yet known whether the spill had any significant longer-term impact on turtle populations in the Gulf of Mexico.

Other reptiles include marine iguana, crocodiles, alligators and sea snakes, which occupy the sea's surface, shallow waters and shorelines. There are potential routes for oil exposure but limited information on the effects of oil on them due to few studies.

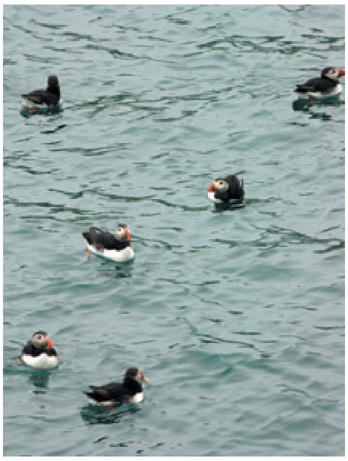
Birds

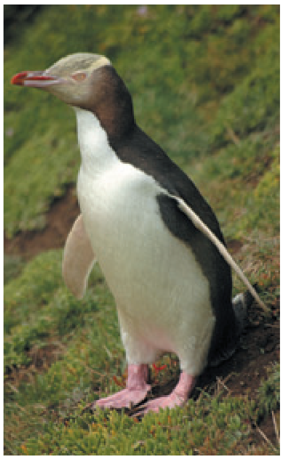
Birds that sit on the water are vulnerable to oil slicks. Many seabirds congregate, particularly during their breeding season, and even a small spill can result in a high mortality if it happens at that time and place.

Oil can impact birds via three pathways, i.e. through physical oiling of their feathers, which can result in hypothermia and reduced capability to move, feed etc.; through ingestion of oil while preening or consuming contaminated food; and via transfer of oil to eggs and young which may result in reduced survival. Distressing images of dead and disabled seabirds with oil coating their feathers have been the enduring legacy of a number of oil spills, and on some occasions the numbers of confirmed bird casualties have reached the tens of thousands. As the recorded number of corpses and live oiled birds is inevitably an underestimate, particularly for spills in remote locations, the actual impact cannot be described accurately, but additional data are sometimes available from population monitoring programmes in some areas. Research into the more subtle sublethal effects of oil contamination, including chronic oil impacts, have also provided more information in recent years.



The vulnerability and sensitivity of birds and bird populations to oil spills varies greatly between species and life stages, and to a large extent their vulnerability is based on the amount of time that they spend on the surface of the water. Many seabirds, such as terns, gannets and shearwaters, and shore birds like oystercatchers, curlew and plover, spend little or no time sitting on the water. The numbers of oil spill casualties of those species, relative to the local populations, are typically low. However, auks (from the family Alcidae, which include guillemots and razorbills), sea duck and grebes, which spend the majority of their life on the water, are much more likely to be oiled





Auks, like these puffins and guillemots (far left and centre), spend a great deal of time on the water and are therefore vulnerable as well as sensitive to oil slicks. Some auks nest in large colonies and congregate on the water at certain times of the year. Penguin colonies (near left) are also highly vulnerable to oil spills.

if a surface slick arrives in the area where they are present. Populations of those species that aggregate on the water in particular locations at particular times of year are therefore highlighted on oil sensitivity maps. Notable examples include the aggregations of auks close to breeding colonies, particularly in the early spring before the mature birds return to their nesting sites, and near the end of the breeding season when flightless juveniles and moulting adults prepare for their migration offshore. Some sea duck and grebes aggregate before starting their long-distance migrations between high latitude summer breeding sites and warmer winter sites, and at particular refuelling locations en route. Large numbers of common scoter, a sea duck, stop to feed in Carmarthen Bay on the south coast of Wales during the spring and autumn. The Bay was severely impacted during the *Sea Empress* spill in February 1996, near the start of the migration period, and 4,700 scoter were found oiled. This was approximately half of the scoter in the Bay at the time, and approximately 5% of the population in the UK that winter. Annual monitoring of the scoter each November showed greatly reduced numbers for two years, but a return to pre-spill levels after three years. They were also shown to be feeding in areas that had been impacted by the spill, suggesting that there was also a good supply of the seabed bivalves and worms that they feed upon.

Most post-spill studies have documented recovery of regional bird populations to pre-spill levels within five years of a serious oil spill impact, but longer-term impacts have also been reported. For any species that rears a maximum of only one or two chicks per breeding pair per year it is likely

Below left: wading birds, like this variable oystercatcher, do not sit on the water, so are less vulnerable to direct contact with oil. Numbers of casualties are usually relatively low and recovery is rapid.

Below right: egrets and other birds roosting on an oiled fish trap in Guanabara Bay, near Rio de Janeiro.


that recovery from a large mortality will take some time unless environmental conditions (habitat, food availability, predation pressure etc.) are ideal. There will be particular concern for the long-term prospects of a population affected by an oil spill if that species is already under threat. Two species of murrelets (Kittlitz's murrelet and marbled murrelet) were affected by the 1989 *Exxon Valdez* oil spill and 1,100 carcasses were recovered. At the time of the spill, Kittlitz's murrelet were already listed on the IUCN Red List and both species have been classified as endangered more recently, with declining populations throughout most of their ranges. The spill had a small but ecologically significant impact on the regional populations of both species at the time, but it was soon apparent that other factors were having a greater impact and it is unclear whether acute mortality from the spill has had a residual effect.

Some seabirds, like these white-fronted terns, nest and roost in locations that would be vulnerable to disturbance from spill response activity.

Recovery of bird populations is also greatly influenced by complex species-specific behaviour. Important factors include sub-population groupings, territories, birds returning to the same site year after year and non-breeding birds. This can result in the slow recovery of a population in one area with many vacant nest sites, while the population in a neighbouring area recovers quickly and nest sites are rapidly re-occupied; there may be no apparent effect on breeding numbers because vacated sites are immediately filled by waiting birds.

Experiments have shown that contamination of eggs by oil can reduce embryo survival and hatching success. It has been suggested that this may have a potential impact on bird populations, but field observations suggest that it has had limited ecological significance. Other studies have shown that small amounts of oil, including sheens, on a bird's plumage can damage the fine structure of the feathers and their function, including waterproofing. The direct effect of light oiling on plumage function is unlikely to result in mortality, but the birds can spend a lot of extra time cleaning themselves by preening; this amounts to a loss of time that could be spent on other activities, and also results in oil being ingested. Some species, like many gulls, have very robust digestive systems, but others can be sensitive to small amounts of oil. The potential effects of ingested oil are numerous and can be lethal, depending on the amount and toxicity. A number of studies have described effects on digestive system function, organ damage, anaemia and effects on reproduction, including egg laying and hatching success. While the birds will eventually metabolize and break down hydrocarbon contaminants, PAHs can also accumulate in their tissues for a period of time, and this may result in immunological effects. However, sublethal effects of ingestion are not likely to persist for more than one season.

Brown pelicans recuperating after being cleaned, during the response to an oil spill in Coatzacoalcos, Mexico, in 2005.

Ingestion of oil can also occur during feeding, particularly by birds that feed on mussels and other bivalves that concentrate hydrocarbon contaminants in their tissues, and by scavengers and raptors which are attracted to dead or dying animals on the shore. This is a potentially significant cause of mortality for some species, but sublethal effects are not likely to persist unless there is a significant chronic source of contamination. Where persistent oil residues remain on shorelines that are frequented by birds, there is some potential for chronic exposure through ingestion of contaminated prey. Some studies following the 1989 *Exxon Valdez* oil spill linked biochemical evidence of hydrocarbon exposure (biomarkers) in some birds to persistent shoreline oil residues on some boulder shores. Black oystercatcher and harlequin duck, which forage among intertidal boulders, are more likely to be exposed to chronic oil inputs through ingestion of contaminated prey. However, other studies have shown that inputs from those sources were reduced to very low levels within two or three years and that risks of ecologically significant effects were small. The regional population of harlequin duck had returned to pre-spill levels by 1993, and while the black oystercatcher population was declining there was no difference in reproductive success between oiled and unoiled areas by 1991.

Harlequin duck eat mussels and other invertebrates on shorelines. If the prey are contaminated with oil the duck may receive chronic inputs. The extent to which this had an impact on harlequin duck populations in Prince William Sound after the1989 Exxon Valdez *spill is still debated.*

Indirect effects on bird populations through impacts on food availability have been suggested for some species after some spills, but this remains a theoretical possibility for a worst-case scenario. While a severe localized reduction in a bird's food resource is possible, the limited extent and considerable patchiness of oil spill effects means that it is unlikely for this to occur over a significant proportion of a bird's daily feeding range. Disturbance from extensive oil spill clean-up activities, however, have some potential to affect wetland bird feeding behaviour and thereby impact their ability to feed efficiently. In cold weather, the energy reserves of some birds, particularly migratory species, may already be very low.

Shoreline and coastal habitats

Impacts of oil spills on shorelines are covered in more detail in the IPIECA-IOGP Good Practice Guide on this topic (IPIECA-IOGP, 2015a). Some of the key features are summarized below.

Shorelines comprise a large variety of habitat types, each of which is characterized by a different community of plants and animals. Many of the most sheltered muddy shores are dominated by plants, particularly saltmarshes, halophytes or mangroves, depending on the climate. Algae tend to dominate on sheltered rocky shores, while invertebrate animals dominate on wave-exposed shores. In polar regions many shores are impoverished compared to those in temperate regions due to the physical effects of the sea ice, while coral reefs fringe some open coast tropical shores. Many birds, fish and mammals also utilize shoreline habitats because of the availability of food, substrate, nutrients and shelter.

Shoreline habitats and species will be vulnerable to any coastal oil spill but, as mentioned previously, the scale of the impact and the rate of recovery will be largely defined by the persistence and condition of the stranded oil, which is itself strongly correlated with wave exposure (see page 17). Thus, impacts on open coast shores are typically short term because oil is usually removed rapidly by water movement and recovery of affected species is a function of natural ecological processes. However, natural removal of oil from sheltered shorelines is slower and, in locations where the intertidal substrata is muddy and dominated by marsh or mangroves, oil residues can persist for years, causing long-term impacts. Examples of long-term persistence of oil include saltmarsh and muddy shores in Buzzards Bay, Massachusetts, oiled by the 1969 *Florida* barge spill; saltmarshes in the Magellan Strait, Chile, oiled by the 1974 *Metula* spill; and sheltered tidal flats and halophyte marsh on the Gulf coast of Saudi Arabia, oiled by the 1991 Gulf War spill. Some oil residues are still

Examples of oiled shorelines (clockwise from top left): rocky; sediment; mangrove; and saltmarsh.

present in parts of those shores today, particularly in Saudi Arabia. They each represent a small fraction of the amount that was spilled, and a small fraction of the area that was originally oiled. Furthermore, the remaining oil residues typically develop a highly weathered crust that displays very limited toxicity or are effectively unavailable to most organisms that live in those areas and are resistant to biodegradation.

While all intertidal species can potentially be affected by oil contamination, some are much more sensitive than others. The majority of seaweeds, for example, are naturally protected by a mucous coating that resists oil, while saltmarsh plants are easily smothered and mangroves can be killed by viscous oil that covers a significant proportion of the breathing pores on their aerial roots. The sensitivity of many intertidal animals is similar to that described for seabed animals resulting from oil in water (see *Seabed life* on pages 21–26), but direct physical oiling is an additional exposure pathway that can cause smothering of feeding mechanisms, blocking of burrows and exposure to high concentrations of hydrocarbons over a relatively long duration with potential for sublethal and lethal effects. The latter is illustrated by limpets, a group of snails that are common on rocky shores in most regions: studies have shown that even small amounts of a fresh oil on a limpet's foot will narcotize it so that it falls off the rock and subsequently dies from desiccation or predation. In some spills this has resulted in dramatic reductions in local populations followed by rapid growth of opportunistic green algae (see examples in IPIECA-IOGP, 2015a). Recolonization of the limpets from planktonic larvae occurs quickly, but full recovery of the community typically occurs within two to three years, and may take five years or longer in rare cases involving severe oiling.

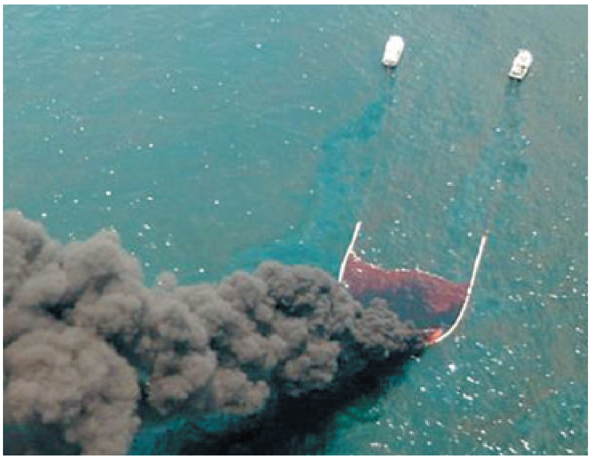
Burrowing crabs are a common feature of many tropical and subtropical sedimentary shores, particularly in mangroves. Oil spills can have severe impacts on these populations, and in addition the burrows create a pathway for oil to penetrate below the surface, leaving persistent residues.

Managing oil spill response and potential impact

Oil spill response is multifaceted and can involve large-scale operations with many potential influences on the marine environment. Response actions can include significant changes in the management of many local marine resources, for example the temporary closure of fisheries and other activities that have prolonged effects on those resources. Experience from past spill responses has shown that it is possible to cause damage with inappropriate treatments ('treatment' is used here to include all clean-up techniques) and that many potential impacts have been associated with the deployment of large numbers of workers, vehicles and vessels. However, many hard lessons have been learnt and modern approaches, techniques, technology, management and planning for oil spill response are now highly advanced. The continuous requirement for trained and experienced personnel is also being addressed and modern oil spill contingency plans include training regimes as an essential component. Good practice guidance documents, including those available in this series, provide information on planning, spill management and the appropriate use of the various treatment techniques. Although many challenges still remain, the appropriate responses can greatly reduce the impacts of an oil spill.

Many of the most serious impacts associated with spill response are due to inappropriate shoreline clean-up. While the removal of oil is beneficial, some removal methods can cause long-term impacts and should be deployed only after careful consideration. Potential damage can include physical removal or disturbance of substrata, damage to plant root systems, driving oil into the sediment, spreading oil into other habitats and damage to adjacent habitats used for access. The primary factors that determine the scale of impacts are the type of habitat, the scale of the clean-up activity and the longevity of the species affected. Habitats that are most sensitive to physical damage are sheltered sedimentary habitats dominated by vegetation—i.e. marshes and mangroves. These and other potential impacts of shoreline clean-up are discussed further in the IPIECA-IOGP Good Practice Guide on the impacts of oil spills on shorelines (IPIECA-IOGP, 2015a).

Many marsh communities, such as this saltmarsh oiled by a pipeline spill in 1989, grow on soft muddy sediment and can be damaged by trampling during spill clean-up.


Elastec

An example of controlled in-situ burning. For more information on this topic see IPIECA-IOGP 2015f.

Offshore treatment techniques with the potential for effects on marine ecology include the use of dispersants (see pages 41–42) and controlled in-situ burning. The latter has been applied to offshore slicks where it is possible to keep the oil thick enough to sustain the burn, including spills on ice. It produces large volumes of smoke, with implications for air quality, which dissipates rapidly and is not expected to have significant impacts when in-situ burning is properly implemented. Burnt residues may float or sink depending on the characteristics of the oil. Studies have shown that burnt residue is less toxic than weathered oil to aquatic biota, but where it sinks (e.g. as mentioned on page 25 in relation to the impacts of the 1991 *Haven* spill in Italy) it could smother benthic organisms that come into direct contact with it. There is potential for chronic toxicity from heavy metals and high molecular weight PAHs remaining in these residues, but the available evidence suggests that they are mostly trapped within the residue matrix and would therefore have low bioavailability. More information is available in the IPIECA-IOGP Good Practice Guide on controlled in-situ burning (IPIECA-IOGP, 2015f).

Restoration activities may be considered the last stages of an oil spill response. While natural recovery of a severely damaged habitat will take place eventually, enhancement of these processes through restoration may be appropriate if the natural rate of recovery is considered to be too long. Direct restoration methods have been successfully developed for certain habitats with dominant species that provide their structure, in particular some saltmarsh and mangrove habitats. These are discussed further in IPIECA-IOGP, 2015a. There has also been some success with restoration of coral reefs and seagrass beds.

Other spill response activities that have relevance to marine ecology are covered in the IPIECA-IOGP Good Practice Guides on wildlife response preparedness (IPIECA-IOGP, 2014a) and shoreline assessment (SCAT) surveys (IPIECA-IOGP, 2014b).

Net environmental benefit analysis

During the response to an oil spill, many operational decisions are made by the incident management personnel to select actions that will remove or treat oil and reduce the overall damage or the threat of damage to affected resources. Some of those actions can have significant implications for the environment and for socio-economic resources. A net environmental benefit analysis (NEBA) is a process that objectively considers the potential benefits and drawbacks of the feasible clean-up/treatment options and compares them with a 'leave-alone' response. Sometimes this can result in decisions that require a trade-off between different environmental and socio-economic concerns. However, a key objective will be to minimize long-term impacts by identifying situations that could result in persistence of the oil and evaluating response options to reduce that risk. There is no single NEBA tool or methodology which is suitable, or indeed appropriate, for application in all situations, but the basic evaluation steps can be summarized as shown in Table 1, in accordance with the IPIECA-IOGP Good Practice Guide on the use of NEBA in developing a response strategy (IPIECA-IOGP, 2015b).

Table 1 *Typical NEBA steps involved in the contingency planning process*

NEBA step	Description
Evaluate data	The first stage is to consider the likely spill location and where it will drift under the influence of currents and wind—various oil spill trajectory models exist to support this. It is also useful to know how an oil will 'weather' as it drifts. This is part of evaluating the available data.
Predict outcomes	The second stage is to assess what is likely to be affected by the spilled oil if no response is undertaken. This may include ecological resources offshore, nearshore and on shorelines, alongside socio-economic resources. The efficiency and feasibility of the response toolkit should also be reviewed. This covers the response techniques, the practicalities of their utilization and how much oil they can recover or treat. If areas under threat include oil-sensitive coastal habitats, the role of oil spill response at sea is to either prevent or limit the spilled oil from reaching these habitats. Previous experience can help to assess which oil spill response techniques are likely to be effective. Pragmatic, operational considerations should form a very important part of the NEBA process applied to all feasible response techniques.
Balance trade-offs	The advantages and disadvantages of the potential response options are considered and weighed against the ecological and socio-economic impacts of each to understand and balance the trade-offs.
Select best options	The process concludes with the adoption of response technique(s) within oil spill contingency plans that minimize the impact of potential spills on the environment, and promote the most rapid recovery and restoration of the affected area.

The benefits and impacts of dispersant application

Dispersants are chemical agents that, when appropriately applied to floating oil, will enhance its dispersal as small droplets into the upper water column, thereby reducing the amount of surface oil. The dispersed oil is rapidly diluted to levels which pose a low toxicity risk and facilitate biodegradation (see *The fate of oil* on pages 9–14). Studies have also shown that dispersants reduce the adhesion of oil to sediments, rocks and biota. By significantly reducing the amount of surface oil there is generally less risk of physical oiling of surface wildlife and shorelines, etc. and, crucially in many situations, a reduced potential for persistent oil residues. Both of these, particularly the latter, will reduce the potential for long-term impacts. However, by enhancing the dispersal and dilution of oil into the upper water column there will be temporary elevated concentrations of hydrocarbons. Carrying out a NEBA for the proposed application of dispersant should therefore assess whether such a response can provide a significant reduction in surface oil, whether that reduction will significantly reduce the potential for persistent oil and impacts on surface and shoreline wildlife and habitat, and whether the increased concentration of oil in the water presents significant risks to fish, shellfish and other aquatic life. Regulations for dispersant use typically pre-authorize the use of approved products in deeper waters (e.g. 10–20 m); special authorization is needed for use in shallow water if it is considered that the benefits could outweigh the impacts.

Figure 6 *The typical biodegradation process for spilled oil following the application of dispersant*

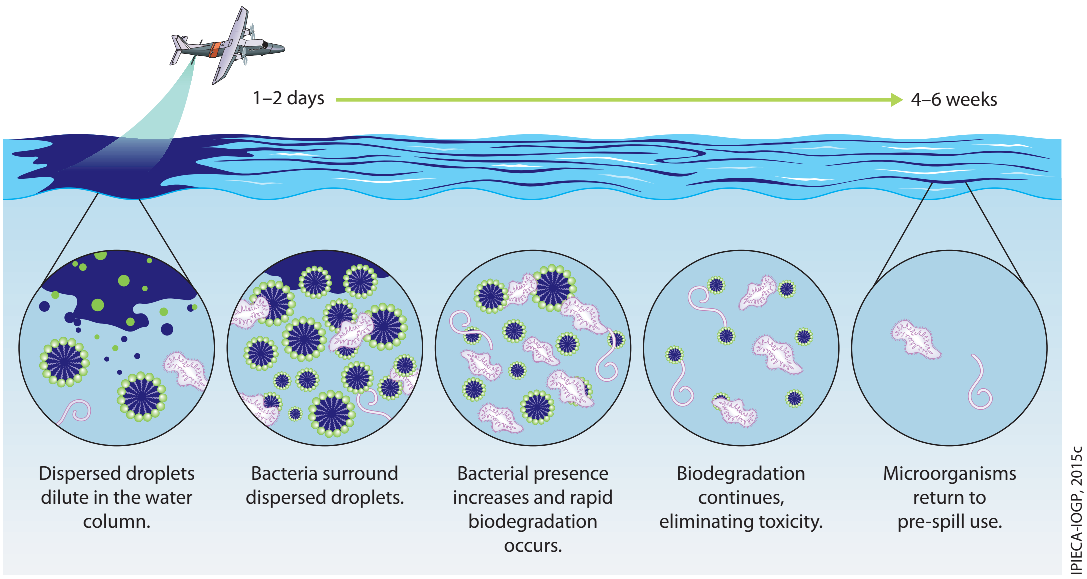
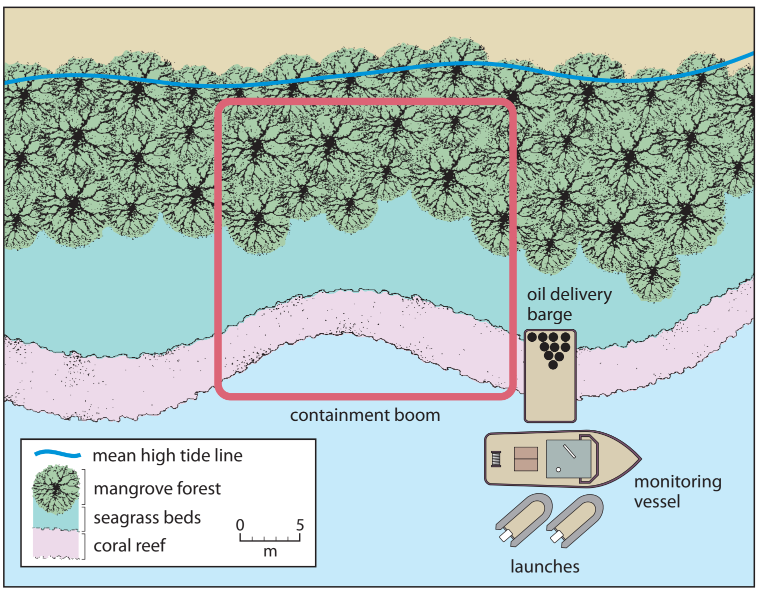


Figure 6 illustrates the biodegradation process for spilled oil following dispersant application on the surface of the slick.

Three large field experiments were carried out in the 1980s to compare the effects of chemically dispersed and undispersed oil in nearshore areas—i.e. the Arctic, and temperate and tropical climates. The first was the Baffin Island Oil Spill (BIOS) project (1980–83) in Canada's eastern Arctic. The second was the Searsport experiment (1981) in Maine on the northeast coast of the USA. The third was the TROPICS study (1984) on the Caribbean coast of Panama (illustrated in Figure 7). Each study included pre-spill and post-spill surveys of the habitats and communities, and of hydrocarbon concentrations in water, sediment and biota. In addition to the habitat differences (from ice-affected shores and seabed to mangroves and coral reefs), there were differences in some of the objectives and designs of the three experiments. However, they all concluded that dispersant application could reduce shoreline oiling and did not result in significant subtidal impacts or persistent sediment contamination. Long-term monitoring continued for some years after the studies, particularly for the TROPICS study where the most recent surveys described persistence of oil and associated impacts on mangroves, for up to 25 years, in areas that were affected by the undispersed oil.

Figure 7 *The 1984 TROPICS study showed some of the potential benefits of dispersant use*



ITOPF

The use of dispersants was a major factor in reducing the volume and geographic spread of shoreline oiling following the grounding of the Sea Empress *in 1996.*

During the 1996 *Sea Empress* spill, a large-scale dispersant spraying operation greatly enhanced dispersion of a significant proportion of the 72,000 tonnes of light crude. It is estimated that around half of the oil was dispersed into the water column, compared to around one-fifth or less if dispersant had not been used. The elevated concentrations of oil in water resulted in impacts on seabed life (see pages 21–26) but recovery of those resources was rapid and there was no persistent contamination of subtidal sediments. It was estimated that the combination of natural and chemical dispersion prevented a potential 120,000 tonnes of emulsion from coming ashore, rather than the 10,000–15,000 tonnes that actually stranded. The dispersant operation was a major factor in reducing both the volume of shoreline oiling and its geographic spread.

Subsea dispersant application is a relatively novel technique that was used during the 2010 Macondo well incident in the Gulf of Mexico. It dispersed a large amount of oil that would otherwise have reached the surface and would have had potentially greater impacts on surface life and shorelines. Studies into the fate of the oil in the water column showed that biodegradation by bacteria was occurring rapidly, thereby greatly reducing the potential for persistent residues in the water or sediments. Research is ongoing into the fate of oil from the spill.

More information on this topic can be found in the IPIECA-IOGP Good Practice Guides on the application of dispersants, both on the surface and subsea; see IPIECA-IOGP 2015c and 2015d, respectively.

Oil spill damage assessment—key activities

Marine oil spills may be high-profile events that can result in environmental impacts and affect the lives of many people. It is understandable that interest will be expressed by both individuals and organizations in knowing what damage was done and how long it will take to recover. Most countries have regulations and policies that require some level of assessment of the impact on commercial fish stocks and fisheries, air, water and sediment quality, sites designated for nature conservation, protected species and human health. However, while government agencies may have environmental quality monitoring programmes in place for routine assessment, these will not be designed for large-scale pollution incidents. Guidance documents on how to carry out an oil spill damage assessment are available for some countries and regions, and the International Maritime Organization and United Nations Environment Programme have jointly produced an international guidance document (IMO/UNEP, 2009). Some of the fundamental requirements are described below.

Pre-spill data on marine communities that have been impacted by a spill is often limited or non-existent. Biologists therefore begin the process of collecting information from oiled areas as soon as possible, as part of an impact assessment.

Acquiring good baseline pre-spill data can be logistically and financially challenging. The highest priority is to collect pre-spill data on hydrocarbon contamination. For many spills there is usually some potential to collect pre-impact samples of water, sediment and biota (particularly commercial species) in the expected path of the oil. It is also important to collect samples of the source oil when it is fresh at the start of the spill and also at intervals from different habitats as it weathers. Rigorous sampling procedures for oils, and oil in waters, sediments and biota, are required to ensure that there is no contamination from other sources. In addition, the subsequent handling and transport of samples to laboratories for analysis needs to comply with strict chain of custody procedures. It will be useful to identify and access any pre-existing data from the area. Environmental data can be accessed via online tools such as the IPIECA Marine Geospatial Bibliography (http://mgb.ipieca.org).

Pre-spill and pre-impact baseline biological data will also be valuable, particularly if it was collected or updated less than a year before the spill. However, the level of natural fluctuations for many populations and communities can be considerable, so old data may have limited value. For species that are being affected by longer-term change there may also be moving baselines to consider. Recent pre-spill and pre-impact fixed point photographs of habitats and conspicuous communities, particularly aerial images of marsh and mangrove, will also be valuable.

Mapping the distribution of oil from a spill is an essential part of a damage assessment. Much of this can be done with aerial reconnaissance. Aerial photographs of oiled communities can also provide valuable information on their extent and condition.

Information on the distribution and concentrations of oil, over the course of the spill, will be essential for any impact assessment, to provide evidence of exposure. This is often provided by aerial reconnaissance, a programme of sampling (as mentioned above, including water column, shoreline and seabed sampling) and surveys of shoreline oil distribution. The latter are typically carried out using the Shoreline Clean-up Assessment Technique (SCAT), which is designed primarily to provide operational support to shoreline response but can also provide valuable information on the likely exposure of shoreline life to oil. For more information on SCAT see IPIECA-IOGP, 2014b. As many ecological effects studies are necessarily limited to small areas, the broad scale information on oil distribution can also increase its representativeness.

Some of the most conspicuous evidence of oil spill impacts on animals and plants is transitory, and includes dead wildlife, strandings of bivalves, blackened or bleached plants and colonization by opportunists. Records and photographs should be taken as these impacts occur and before the evidence disappears. Dead wildlife should be collected and suitably stored for possible later analysis. For more information on preparing and responding to an oiled wildlife incident refer to the IPIECA-IOGP Good Practice Guide on wildlife reponse preparedness (IPIECA-IOGP, 2014a).

Recording observations of oiled wildlife is an important aspect of a damage assessment. This oiled tortoise was found by clean-up workers during the 1999 Estrella Pampeana *spill in Argentina.*

Clearly-defined aims are essential for a well-organized damage assessment study. This should include a definition of the scope (geographic, time limits, scale of study and end points) and decisions on whether the assessment will focus on defined thresholds, comparisons with baselines, comparisons with reference sites or trends over time. It is important to consider the realistic possibility that even a detailed study may still not provide statistical proof that there was, or was not, an impact. Where damage is evident, there will be a desire to establish the timescales of recovery, but this could become an open-ended activity unless an end point has been defined. A fundamental aim of many studies will be to evaluate the merit of compensation claims.

Logistical and budgetary limitations mean that there will need to be some prioritization of the ecological resources that are to be assessed. Once chosen, the design of the study should then be based on the defined aims. For any particular resource there will be many possible techniques, measurements, sites and sampling schemes to consider.

Where a study finds evidence of an impact, there will also be a need to establish a realistic mechanism (pathway) by which the oil spill could have caused that damage.

As biological and chemical sampling programmes are often carried out by different laboratories or personnel, it is important that the programmes are designed together and that coordination is maintained. This is not always easy to achieve but, for shorelines, detailed information on oil distribution from a SCAT programme can provide a useful common data set that brings studies together and aids their design.

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Useful websites

Deepwater Horizon, Bibliography of Published Research:
www.lib.noaa.gov/researchtools/subjectguides/dwh.html

Exxon Valdez Oil Spill Trustee Council: www.evostc.state.ak.us

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: www.cefas.defra.gov.uk/premiam/publications.aspx

Acknowledgements

This document was authored by Jon Moore (CALM) under the auspices of the Impacts Working Group.

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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.

www.ipieca.org

IOGP International Association of Oil & Gas Producers

IOGP represents the upstream oil and gas industry before international organizations including the International Maritime Organization, the United Nations Environment Programme (UNEP) Regional Seas Conventions and other groups under the UN umbrella. At the regional level, IOGP is the industry representative to the European Commission and Parliament and the OSPAR Commission for the North East Atlantic. Equally important is IOGP's role in promulgating best practices, particularly in the areas of health, safety, the environment and social responsibility.

www.iogp.org.uk