THE SEA EMPRESS OIL SPILL IN CONTEXT

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ABSTRACT

Given the low world-wide incidence of major tanker spills in recent years, the UK can be considered unfortunate to have suffered three of the world's 20 largest spills of all time, two of them only three years apart. The grounding of the *Sea Empress* in February 1996 followed the wrecks of the *Braer* in January 1993 (84,700 tonnes of oil spilled) and the *Torrey Canyon* in March, 1967 (119,000 tonnes). Volume of oil lost, however, is not necessarily the most important factor in determining the seriousness of a particular incident. How the spilled oil behaves, where it ends up and what it affects will normally depend more upon the type of oil; the prevailing weather and sea conditions; and the physical, biological and socio-economic characteristics of the spill location. These in turn can be influenced by the time of the year, as well as the type of clean-up measures adopted, their effectiveness and net environmental benefit.

These inter-acting factors are explored by the authors, with reference to previous major oil spills that have been studied in some depth, in order to provide a basis for assessing the results of the various studies following the *Sea Empress*.

INTRODUCTION

Ever since the *Torrey Canyon* in 1967, major tanker accidents have invariably prompted the same questions about the apparent inefficiency of clean-up techniques, and the nature and extent of impacts on the environment. They include:

- Why is it that there is no technology to prevent spilled oil fouling beaches and damaging wildlife and coastal resources?

- What are the most acceptable clean-up techniques from an environmental point of view?

- What will be the damage to the environment?

- How long will it take for the environment to recover?

Whilst surprisingly few major oil spills have been investigated in a comprehensive manner, we now have a far greater understanding of the issues and it is possible to provide good answers to these questions by looking back at over thirty years' post-spill studies, laboratory experiments, field tests and, in the case of biological impacts, the results of long-term monitoring in high risk areas such as Milford Haven. This body of information provides a basis upon which the results of the studies following the *Sea Empress* can be judged.

This paper aims to highlight some of the key lessons learned from past spills, by reference to a number of case histories.

INCIDENCE OF TANKER SPILLS

Analysis of nearly 10,000 records in ITOPF’s database of oil spills from tankers, combined carriers and barges (“tankers”) world-wide reveals that:

- Over 85% of all spills from tankers are less than 7 tonnes;

- most spills from tankers occur during routine operations such as loading, discharging and bunkering, which normally take place in ports or at oil terminals;
- the majority of these operational spills are small, with some 93% involving quantities of less than 7 tonnes;
- spills over 700 tonnes represent less than 3% of the total number of spills;
- over 62% of all spills over 700 tonnes result from collisions and groundings.

Given the relative ineffectiveness of oil spill combating techniques, the only real solution to minimising environmental and economic damage lies in preventing tanker spills happening in the first place.

Figure 1 illustrates that much has been achieved in this regard over the past three decades. Thus, although there are considerable annual fluctuations, the average number of large tanker spills (over 700 tonnes) world-wide each year in the 1980s

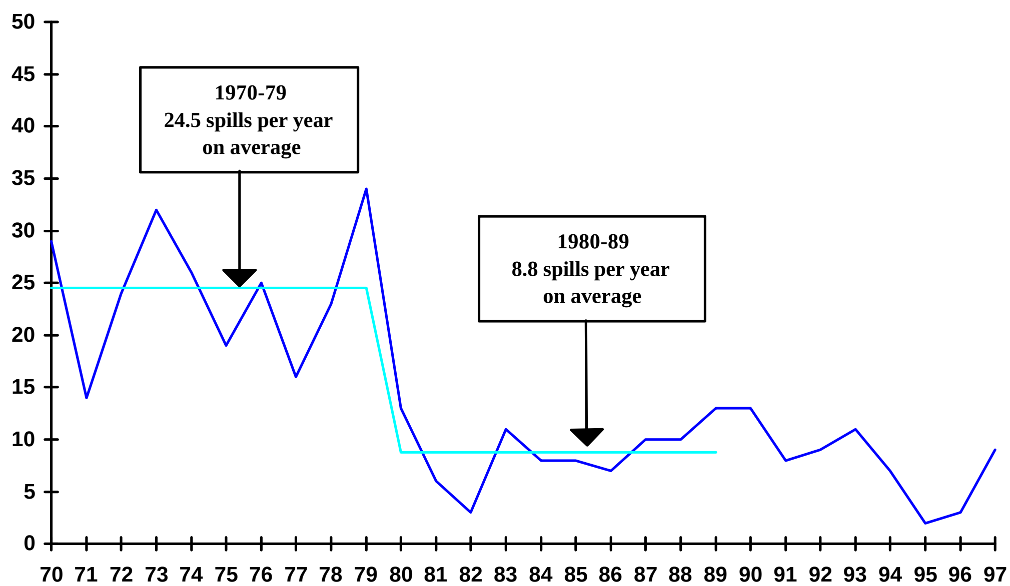

Figure 1. Incidence of tanker spills over 5000 barrels (700 tonnes), 1970 - 1997

and continuing through to 1997 was about one-third of that experienced in the 1970s. The average annual amount of oil lost as a result of tanker accidents has also been reduced since the beginning of the 1970s and now represents less than 0.01% of the total quantity transported by sea each year.

The UK can be considered very unfortunate to have suffered three of the world's 20 largest tanker spills of all time, two of them only three years apart (see Table 1). Volume of oil lost, however, is not necessarily the most important factor in determining the seriousness of a particular incident. This is well illustrated by the *Exxon Valdez*, which ranks only about 34th in terms of size but is undoubtedly very near the top of the list of the most significant, and certainly most expensive, tanker spills of all time.

How spilled oil behaves, where it ends up and what it affects normally depends more upon the type of oil, the prevailing weather and sea conditions, and the physical, biological and socio-economic characteristics of the spill location. These in turn can be influenced by the time of year, as well as the type of clean-up measures adopted [1].

Table 1. The World's Largest Tanker Spills, 1960-1997

DATE	NAME	TONNES	OIL TYPE	LOCATION
19/07/79	*Atlantic Empress*	287,000	Crude	10 nautical miles east of Tobago
28/05/91	*ABT Summer*	260,000	Crude	700 nautical miles off west coast of Angola
06/08/83	*Castillo de Bellver*	252,000	Crude	70 nautical miles north west of Cape Town, South Africa
16/03/78	*Amoco Cadiz*	223,000	Crude	Brittany, France
11/04/91	*Haven*	144,000	Crude	Off Genoa, Italy
10/11/88	*Odyssey*	132,000	Crude	700 nautical miles off Nova Scotia, Canada
18/03/67	*Torrey Canyon*	119,000	Crude	Off the Scilly Isles, UK

19/12/72	*Sea Star*	115,000	Crude	Gulf of Oman
12/05/76	*Urquiola*	100,000	Crude	La Coruña, Spain
23/02/77	*Hawaiian Patriot*	95,000	Crude	325 nautical miles west of Honolulu, Hawaii
15/11/79	*Independenta*	94,600	Crude	Off Istanbul, Turkey
29/01/75	*Jakob Maersk*	88,000	Crude	Leixoes, Portugal
05/01/93	*Braer*	84,700	Crude	Shetland, UK
19/12/89	*Khark 5*	80,000	Crude	120 nautical miles off Atlantic coast of Morocco
03/12/92	*Aegean Sea*	73,500	Crude	Off La Coruña, Spain
15/02/96	*Sea Empress*	72,000	Crude	Off Milford Haven, UK
16/04/92	*Katina P.*	72,000	Heavy fuel oil (cargo)	Off Maputo, Mozambique
06/12/85	*Nova*	70,000	Crude	75 nautical miles south of Kharg Island, Iran
01/05/75	*Epic Colocotronis*	60,000	Crude	60 nautical miles north west of Puerto Rico
06/12/60	*Sinclair Petrolore*	60,000	Crude	Off Brazil

FATE OF MARINE OIL SPILLS

When oil is spilled onto the surface of the sea it spreads very rapidly. After a few hours the slick will usually also begin to break up and form narrow bands or "windrows" parallel to the wind direction.

Within a very short time, therefore, the oil will often be scattered within an area of many square nautical miles with large variations in oil thickness being evident. At the same time as the oil spreads, moves and fragments it also undergoes a number of chemical and physical changes, collectively termed weathering.

Most of the weathering processes, such as evaporation, dispersion, dissolution and sedimentation, lead to the disappearance of the oil from the surface of the sea, whereas others, particularly the formation of water-in-oil emulsions ("mousse") and the accompanying increase in viscosity, promote its persistence. The speed and relative importance of the processes depends on factors such as the quantity and type of oil, the prevailing weather and sea conditions, and whether the oil remains at sea or is washed ashore. Ultimately, the marine environment assimilates spilt oil through the long-term process of biodegradation.

In considering the fate of spilled oil at sea, the need for clean-up and the nature of likely impacts, a distinction is frequently made between non-persistent oils and persistent oils. Non-persistent oils include light refined products (e.g. petrol) and even some light crude oils which are highly volatile materials with low viscosities.
As they do not normally persist on the sea surface for any significant time due to rapid evaporation and the ease with which they disperse and dissipate naturally there is usually only a limited requirement for clean-up, as demonstrated by the *Dona Marika* spill in Milford Haven in 1973. Such oils may, however, pose a significant fire and explosion hazard as well as public health concerns. They can cause significant environmental impacts due to their high concentration of toxic components, but as these same components evaporate rapidly any such effects will be very localised.

At the other end of the spectrum of oil types are heavy crudes, heavy fuel oils and other oils which form stable water-in-oil emulsions. These oils are highly persistent when spilled due to their greater proportion of non-volatile components and high viscosity. Such oils have the potential, therefore, to travel great distances from the original spill location, causing widespread contamination of coastlines and damage to amenity areas, fishing gear and wildlife, mainly through physical smothering. As a consequence, the clean-up of heavy oil spills can be difficult and extend over large areas. This is well illustrated by the recent *Nakhodka* spill in Japan and, longer ago, by the *Tanio*, which broke up off the north coast of Brittany, France in 1980. In this latter case the clean-up of the resulting spill of some

14,500 tonnes of the heavy fuel oil cargo was in many ways just as difficult as for the 223,000 tonnes of crude oil from the *Amoco Cadiz* which had contaminated the same coastline two years earlier.

Knowledge of the type of oil and predictions of its probable movement, behaviour and fate are vital in order to determine the most appropriate response measures. The various options are described in many publications [2][3] and are summarised below.

OIL SPILL CLEAN-UP TECHNIQUES

A clean-up response is not always necessary. If modelling indicates that the oil will remain offshore where it will dissipate and eventually degrade naturally without affecting coastal resources or wildlife, monitoring the movement and fate of the floating slicks to confirm the predictions may be sufficient. On this basis, many of the largest tanker spills over the last 20 years, including the *Atlantic Empress, ABT Summer, Castillo de Bellver, Odyssey and Hawaiian Patriot* did not require a major clean-up response. In other cases, like the *Braer,* a combination of light crude oil and severe weather conditions can also dramatically reduce the need for a clean-up response, even when very large quantities of oil are spilled close to the coastline.

Containment and recovery

When a response at sea is considered necessary, the use of booms to contain and concentrate floating oil prior to its recovery by specialised skimmers is often seen as the ideal solution since, if effective, it would remove the oil from the marine environment. Unfortunately, this approach suffers from a number of fundamental problems, not least of which is the fact that it is in direct opposition to the natural tendency of the oil to spread, fragment and disperse under the influence of wind, waves and currents. Thus, even if containment and collection systems are operating within a few hours of an initial release they will tend to encounter floating oil at an extremely low rate. Wind, waves and currents, even quite moderate ones, also limit the effectiveness of collection systems on the open sea by making correct deployment difficult and causing oil to splash over the top of booms or be swept underneath. Because of this it is rare, even in ideal conditions, for more than a relatively small proportion (10-15%) of the spilled oil to be recovered from open water situations. In the case of the

Exxon Valdez, where enormous resources were dedicated to offshore oil recovery, the percentage was at most 9% [4][5].

While at-sea recovery rates may be low when viewed as a percentage of the total volume spilled, the benefit of such operations can be maximised by targeting the heaviest oil concentrations and areas where collection will reduce the likelihood of oil impacting sensitive resources. Greater overall success can also be achieved by containment and recovery operations in sheltered coastal areas and where floating slicks are concentrated within port areas or by natural features.

In-situ burning

An alternative technique involves concentrating the spilled oil in fireproof booms and setting it alight. In practice, it is usually difficult to collect and maintain sufficient thickness of oil to burn and because the most flammable components of the spilled oil will evaporate quickly, ignition can also be difficult. Residues from burning may sink, with potential long-term effects on sea bed ecology and fisheries. Closer to shore or the source of the spill, there may be health and safety concerns as a result of the risk of the fire spreading out of control or atmospheric fall-out from the smoke plume. The most promising area for *in-situ* burning is probably the Arctic and similar areas where spilled oil may be trapped in pools among the ice.

Dispersants

The main alternative to containment and recovery is the use of chemical dispersants. Dispersants work by enhancing the natural dispersion of the oil into the water column. The oil is broken down into tiny droplets which are rapidly diluted, carried away by currents and eventually broken down by micro-organisms.

As with containment and collection, the rapid spreading and fragmentation of oil spilt on the open sea tends to work counter to the effective application of dispersants. However, the likelihood of success can be increased by using aircraft which are able to deliver the chemical more rapidly than ships and with greater precision on to the thickest concentrations of oil or those slicks posing the most significant threat to sensitive resources. For maximum effectiveness, dispersants need to be applied to oil near to the source and before it has become viscous through evaporation or formed an emulsion. Some types of oil such as heavy fuel oil and viscous crude are less amenable to dispersion from the outset.

The use of dispersants is strictly controlled in most countries because of concerns over increasing the oil's impact on fisheries and on sensitive fauna and flora in the water column or on the sea bed in shallow waters. However, the controlled use of dispersants can, in many situations, result in a net environmental benefit, as discussed later in this paper.

Protecting sensitive resources

Given the difficulties of cleaning up oil at sea, coastal resources can often be threatened. Protective measures can include closing water intakes to industrial plants or coastal lagoons. It may be possible to protect other sensitive areas by the careful deployment of booms. In such cases highest priority is usually given to those environmental and economic resources which are particularly sensitive to oil pollution and which can be boomed effectively.

Whilst some sites will be relatively easy to protect, others such as marshes, mangroves and amenity beaches are often too extensive for booming to be practical. It is important to act quickly and, with limited resources available, decisions must be taken as to which sites should be given priority. This should be pre-determined, in contingency plans, with the feasibility of planned deployments regularly tested.

Shoreline clean-up

It is impossible to protect an entire coastline and every sensitive resource with equal success and so in a major oil spill some contamination of coastal areas is virtually inevitable, unless winds and currents carry the oil offshore. The removal of floating oil from harbours and elsewhere where it becomes concentrated is relatively straightforward, using a combination of specialised booms and skimmers and locally available resources such as vacuum trucks and similar suction devices, so long as there is good access.

Once oil has impacted shorelines, a combination of clean-up techniques is normally used, including manual and mechanical removal, flushing or washing with water at high or low temperatures and pressures, and even wiping with rags and sorbent materials. Such operations generally rely on locally-available non-specialised equipment and manpower. Shoreline clean-up is often highly labour intensive and not a 'high-tech' business.

Some types of coastline, such as hard packed sandy beaches, are relatively easy to clean whereas others such as cobble beaches can pose considerable problems. It is important to choose techniques which are appropriate for a particular shoreline type and the level of oil contamination, with effort first directed to areas which have the heaviest concentrations of mobile oil, which could otherwise lead to further pollution of surrounding areas. It is, however, important to recognise from the outset that inappropriate clean-up measures can cause longer-term damage than the oil pollution itself. The environmental sensitivity of the site and the use to which it is put (e.g. as an amenity beach) will need to be balanced in order to determine the most appropriate approach, as well as the degree of cleaning and its termination [6]. These issues are discussed further later in this paper.

Other key clean-up issues

At-sea recovery and shoreline clean-up generate substantial amounts of oil and oily waste which need to be temporarily stored, transported and ultimately disposed of in an environmentally-acceptable manner. Such operations often continue long after the clean-up phase is over. It is regrettable that insufficient attention continues to be given in many countries to this aspect of spill response at the contingency planning stage.

Whilst the technical aspects of dealing with an oil spill are clearly important, the effectiveness of the response to a major spill will ultimately depend upon the organisation and control of the various aspects of the clean-up operation. Numerous difficult decisions as well as compromises will be required throughout the response operation, and the widely differing requirements of a multitude of governmental and private organisations, as well as public and political pressures will need to be reconciled in a prompt manner. There is a far greater likelihood that this will happen if effort has been devoted beforehand to the preparation of a comprehensive, realistic contingency plan.

BIOLOGICAL AND OTHER IMPACTS

The range of oil impacts after a spill can encompass:

- Physical and chemical alteration of natural habitats, e.g. resulting from oil incorporation into sediments;
- Physical smothering effects on flora and fauna;
- Lethal or sub-lethal toxic effects on flora and fauna;
- Short and longer-term changes in biological communities resulting from oil effects on key organisms, e.g. increased abundance of intertidal algae following death of limpets which normally graze the algae;
- Tainting of edible species, notably fish and shellfish, such that they are inedible and unmarketable (even though they are alive and capable of self-cleansing in the long term);
- Loss of use of amenity areas such as sandy beaches;
- Loss of market for fisheries products and tourism because of bad publicity (irrespective of the actual extent of tainting or beach pollution),
- Fouling of boats, fishing gear, slipways and jetties;
- Temporary interruption of industrial processes requiring a supply of clean seawater.

Evidence published in the scientific literature shows that the nature and extent of damage can vary from minimal (e.g. following some open ocean spills such as the *Argo Merchant* and *Castillo de Bellver)* to the death of everything in a particular biological community. There is no clear-cut correlation between size of spill and damage, as evidenced by fisheries and mariculture data [7] and bird data [8][9]. Stowe's data [8] show the number of birds found dead per tonne of oil ranging from 0 to 740. The figure of 740 dead comes from an extreme case in the Firth of Forth in which a spill of only one tonne (of heavy fuel oil) reached large aggregations of birds.

Recovery

Previous case history evidence is of particular benefit for enabling predictions of recovery - there are many observations (summarised in [10]) on natural oil residence times and biological recovery times for different shore types. Recovery depends upon both removal of oil which is toxic or physically smothering, and biological processes, e.g. settlement of larvae and growth of seedlings. Abundant organisms with highly mobile young stages produced in large numbers may repopulate an affected area rapidly, whereas populations of long-lived, slowly maturing species with low reproductive rates may take many years to recover their pre-spill numbers and age structure.

Complete removal of all oil is not necessary - there are many examples of recovery progressing in the presence of weathered oil residues [11]. Recorded recovery times range from less than one year for some exposed rocky shores, to more than 20 years for some sheltered marshes. The available information has been used to produce shore vulnerability indexes such as [12] which summarise the behaviour of oil on different types of shore and which can be used for predictive purposes and oil spill contingency planning [13].

Misunderstandings sometimes arise because of the use of different criteria to determine 'recovery'. Given the difficulties of knowing exactly what pre-spill conditions were, and how to interpret them in the face of natural ecological fluctuations and trends, it is unrealistic to define recovery as a return to pre-spill conditions. The following definition takes these problems into account:

> "Recovery is marked by the re-establishment of a healthy biological community in which the plants and animals characteristic of that community are present and functioning normally. It may not have the same composition or age structure as that which was present before the damage, and will continue to show further change and development. It is impossible to say whether an ecosystem that has recovered from an oil spill is the same as, or different from, that which would have persisted in the absence of the spill [10]."

Factors which have proved to be important in determining damage and subsequent recovery rates include oil type; oil loading (the thickness of deposits on the shore); local geography, climate and season; relative sensitivity of species and biological communities; local economic and amenity considerations; and type of clean-up response. These factors are discussed in more detail below.

MAIN FACTORS WHICH DETERMINE SERIOUSNESS OF IMPACT

Type of oil

Different crude oils and oil products vary widely in physical and chemical properties, and in toxicity. Experiments on plants and animals have shown that severe toxic effects are associated with hydrocarbons with low boiling points (particularly aromatics) because these hydrocarbons are most likely to penetrate and disrupt cell membranes. The greatest toxic damage has been caused by spills of lighter oil, particularly when confined to a small area, e.g. the No. 2 fuel oil spill from the *Florida* [14] and the petrol spill from the *Dona Marika* in Milford Haven [15]. Oil toxicity is reduced as the oil weathers and the most toxic components are lost by evaporation. Thus a crude oil that quickly reaches a shore is more toxic to shore life than oil that has weathered at sea for several days before stranding.

Lighter oils are also more likely to penetrate into sediments and affect infauna, whereas spills of viscous heavy oils, such as some crudes and heavy fuel oil, may blanket areas of shore and kill organisms primarily through smothering (a physical effect) rather than through acute toxic effects. This is also the case with viscous water-in-oil emulsion ("mousse"). Thick layers of oil or mousse may, with incorporated sand, gravel and stones, harden into relatively persistent asphalt pavements (as happened, for example, following the *Metula* spill).

Weather and sea conditions

High temperatures and wind speeds increase evaporation, which leads to a decrease in toxicity of oil remaining on the water. Temperature affects the viscosity of oil (and so the ease with which it can be dispersed, and with which it can penetrate into sediments). Temperature, together with oxygen and nutrient supply, determines the rate of microbial degradation which is the ultimate fate of oil in the environment. Sea state (partly dependent on wind conditions) has a bearing on dispersion or emulsification of oil. For example, there was spectacular natural dispersion of light crude oil in very rough seas following the grounding of the *Braer,* whereas choppy conditions following the *Metula* spill helped produce large volumes of water-in-oil emulsion from a medium crude oil.

Physical characteristics of the area

With oil on the water, damage is likely to be more pronounced in shallow bays and inlets, where there is less scope for natural dispersion and dilution of oil than in the open sea. Once stranded on the shore, wave energy levels are of particular importance. On exposed rocky shores, effects on shore life tend to be minimal and recovery rates rapid because oil is likely to be quickly cleaned off by vigorous wave action. With increasing shelter of shores, the likelihood of oil persisting increases, as does the biomass with its capacity to trap oil. The most sheltered shores tend to be sedimentary, with mud flats and saltmarshes. Marshes have a high biological productivity but are also the worst oil traps, and are therefore of particular concern following spills.

If oil penetrates into the substratum, residence times are likely to be increased. The extent to which this can happen varies with substratum type. Shores over a range of energy levels with freely draining sand, gravel or stones are porous, and oil penetrates relatively easily. If it then becomes adsorbed onto the large surface area of the sub-surface grains, and weathers *in situ* to become more viscous, it may remain in the sediment for many years. In contrast, oil does not penetrate readily into firm waterlogged fine mud or sand and so it tends to wash off with subsequent tidal immersions. However, the picture may be very different on sheltered sand and mud shores with high biological productivity. Oil pathways are provided by the burrows of worms, molluscs and crustaceans, and the stems and roots of plants. Under normal conditions, these pathways allow the penetration of oxygen into sediments that would otherwise be anaerobic. A possible problem following oiling is that there is sub-surface penetration of the oil, followed by death of the organisms that normally maintain the pathways. The pathways then collapse, e.g. burrows become filled in with sediment from the top if they are not actively maintained. Thus oil can be trapped in anaerobic sediment, where its degradation rate will be very low, and organisms trying to re-colonise may encounter toxic hydrocarbons. In these conditions, oil-tolerant opportunistic species are favoured.

Biological characteristics of the area

Different species have different sensitivities to oil, and reduced abundance of vulnerable key species can lead to indirect effects on biological communities. Comments on the main groups of plants and animals are given below.

Low concentrations of oil have been shown to affect various plankton species in laboratory toxicity tests, but studies following oil spills have failed to detect significant, long-term effects on plankton in the open sea. This is probably because high reproductive rates and immigration from outside the affected area counteract short-term reductions in numbers caused by the oil.

Oil does not readily penetrate most seaweeds because of their mucilaginous coating, and there are many cases of the larger seaweed species surviving oil pollution. However, some seaweeds e.g. *Porphyra* (laver bread) may be used for food and following a spill there may be problems of tainting, and subsequent economic loss.

Saltmarshes are sheltered 'oil-traps' where oil may persist for many years. In cases where perennial plants are coated with relatively thin oil films, recovery can take place through new growth from underground stems and rootstocks. Annual plants are more sensitive because they do not have such underground reserves. In extreme cases of thick smothering deposits, recovery times may be decades [16]. In the tropics, mangroves often occur on sheltered sedimentary shores, and are particularly sensitive as demonstrated, for example, by the *Funiwa V* and Bahia Las Minas spills.

Molluscs are often oiled following spills, and there have been several cases where herbivorous species (notably limpets), and infauna (notably razor shells) have suffered heavy mortalities after spills of fresh crude. In contrast, there are many observations of littorinid winkles surviving contact with heavy or weathered oils. Tainting can be a problem both in the case of species gathered from the wild for human consumption, and in the case of cultured molluscs such as oysters. Oiling of cultured molluscs can result in severe (but not permanent) economic damage.

Intertidal crustaceans, notably barnacles, may suffer heavy mortalities if oiled but case history evidence suggests that recovery of populations, by settlement of tidally-dispersed planktonic larvae, is usually good. Sub-tidal and water column crustaceans are less likely to come into contact with oil, although amphipods do seem to be particularly sensitive. Tainting is a particular problem with cultured crustaceans such as prawns.

Fish eggs, larvae and young fish are comparatively sensitive as demonstrated in laboratory toxicity tests, but there is no definitive evidence which suggests that oil pollution has significant effects on fish populations in the open sea. This is partly because fish can take avoiding action and partly because oil-induced mortalities of young life stages are often of little significance compared with huge natural losses each year (e.g. through predation). There is an increased risk to some species and life stages of fish if oil enters shallow nearshore waters which are fish breeding and feeding grounds. Fish held in cages are unable to avoid floating slicks or high concentrations of dispersed oil, although mortalities as a result of contamination are extremely rare. Tainting may, however, make the fish inedible and unmarketable.

Seabirds are extremely sensitive to oiling, with high mortality rates of oiled birds. Moreover, there is experimental evidence that small amounts of oil transferred to eggs by sub-lethally oiled adults can significantly reduce hatching success. Shore birds, notably waders, are also at risk though are less likely to become seriously and lethally oiled than seabirds such as guillemots and cormorants. Worst-case scenarios would include oil impacting feeding grounds at a time when large numbers of migratory waders or sea ducks are in the area.

Marine mammals with restricted coastal distributions and ones that breed on shorelines are more likely to encounter oil than wide-ranging species moving quickly through an area. Species at particular risk are those which rely on fur for conservation of body heat (e.g. otters). If the fur becomes matted with oil, they rapidly lose body heat and die from hypothermia. Whales, dolphins and seals are at less risk because they have a layer of insulating blubber under the skin.

Socio-economic characteristics of the area

Oil spill damage and the nature of any clean-up response depend partly on the relative importance of socio-economic considerations including the following.

- A spill can result in lost fishing opportunities if fishermen are unable or unwilling to fish because of the risk of fouling boats and gear, or tainting the catch. Finfish and shellfish exposed to crude oil or its products may become tainted and unfit for sale if oil-derived substances absorbed by the tissues impart unpleasant odours and flavours. Exclusion zones where fishermen are banned from fishing for particular species may be imposed until the target species has been declared taint-free by chemical analysis and 'blind' taste testing using trained panels. Farmed fish and shellfish may have to be destroyed if they cannot reach the market at the right time because of tainting. All these consequences of a spill can have serious economic impact, as in the *Braer* [17][18] and numerous oil spills affecting mariculture facilities in the Far East and elsewhere [7][19].

- Coastal amenities and tourist facilities include beaches and park areas. Marinas and jetties provide facilities for pleasure boat use, and some fishing and angling activities serve the tourist trade. Oil may temporarily render such resources unusable. Moreover, the reputation of affected areas may suffer, such that tourist bookings are lost even for periods after the oil has been cleaned up. This can be a particular problem if media interest at the time of the spill is great and there is no follow up when clean conditions return. The sensitivity of parks is high because these areas are particularly likely to contain sensitive resources such as birds and mammals; and some parks are an attraction for 'ecotourists'.

- Some industries abstract sea water for cooling or other purposes, and some countries rely on desalination plants for drinking water. Oil entering the industrial or desalination plant with the abstracted water can have serious effects, though the risk of this is reduced if the intakes are in deep water or they can be protected with floating booms.

Time of year/season

According to season, vulnerable groups of birds or mammals may be congregated (perhaps with young ones) at breeding colonies, and fish may be spawning in shallow nearshore waters. Winter months may see large groups of migratory waders and sea ducks feeding in estuaries and coastal areas. Winter oiling of a saltmarsh can affect over-wintering seeds and reduce germination in the spring. Marked reduction of flowering can occur if plants are oiled when the flower buds are developing; even though there may be good vegetative recovery, there is loss of seed production for that year. Tourism impacts will also vary according to the time of the year, with losses greatest as a result of spills at the start of the main tourist season. Similar seasonal factors will apply to fisheries, especially those based on migratory species.

Clean-up

According to circumstances, clean-up efforts can decrease or increase damage. Decisions frequently have to be made between different, conflicting environmental concerns, or between environmental and economic concerns. Weighing up the advantages and disadvantages of any clean-up method is known as net environmental benefit analysis, and this should be considered as part of the contingency planning process. Some examples are given below. In many cases, the predicted natural cleaning times may be acceptable, either because they are short, or because, even if long, no net environmental benefit can be predicted by intervention.

Physical removal of bulk oil, or 'free' oil from shorelines, e.g. by flushing or washing, can decrease damage by limiting the threat to some types of organism, by reducing the likelihood of oil floating off and threatening other areas, and by averting the formation of asphalt pavements. However, shore clean-up can damage organisms such as mussels, winkles and barnacles. They may be trampled during any type of clean-up activity, or 'cooked' during hot water/steam treatment. Experiments carried out in Sweden in the early 1980s, together with experience in Alaska following the *Exxon Valdez* spill, have shown that high pressure, hot water washing is particularly damaging to shore algae and invertebrates. Nevertheless, it may still be justifiable (as was argued in Alaska) if it minimises the threat to birds and mammals that use the shore. The question which needs to be answered is: what resource has the highest priority?

The removal of residual oil, e.g. stains, weathered crusts, or oil buried in sediments, may be controversial because some people approach the problem from an aesthetic point of view and others from a biological point of view. Biologically there seems little point in disturbing the shore to remove such residues if recovery of flora and fauna is progressing (which is usually the case). It might be justified, however, if residual oil is hindering recovery.

Dispersants are an option for offshore treatment of slicks, and they also have a role in some onshore clean-up operations. All groups of dispersants now used are of low toxicity compared with the old 'first generation' products used during the *Torrey Canyon* spill in 1967. A review of dispersant use, with particular reference to environmental concerns, concluded that in most regions the dispersant option will offer a net environmental benefit for some oil spill scenarios [20]. Because the 'window of opportunity' for most effective dispersant use is typically only one to two days following a spill, it is particularly important to consider advantages and disadvantages of dispersants before a spill occurs. For example, dispersants may break up a slick and so reduce the threat to birds, mammals and shorelines, but the dispersed oil enters the water column. In deep open waters it is rapidly diluted, but there is often concern about the potential effects of the dispersed oil in shallow waters where it may increase the threat to organisms such as fish larvae and sensitive benthic fauna, as well as to shellfish beds and mariculture facilities. For this reason, dispersant use may be prohibited from some areas, and at certain times of year.

CASE HISTORIES

Metula

The *Metula* grounded in the eastern Strait of Magellan, Chile, on 9th August, 1974. About 47,000 tonnes of light Arabian crude oil and 3,000 to 4,000 tonnes of heavy fuel oil are estimated to be have been lost. Large volumes of emulsion were produced in the rough sea conditions and much of this landed on shores of northern Tierra del Fuego. Most of the shores affected were of mixed sand and gravel, but two small estuaries including saltmarshes were also oiled. About 4,000 birds are known to have been killed, including cormorants and penguins. No clean-up was done because of the remoteness of the area, and consequently this remains a spill site of foremost distinctiveness and interest for investigating the long-term fate and effects of heavy oiling. One very sheltered marsh received thick deposits of mousse and, in December 1993, these deposits still were visible on the marsh surface, with the mousse quite fresh in appearance beneath the weathered surface skin. Little plant re-colonisation has occurred in the areas with thicker deposits with a mean oil depth of 4 or more cm, though it is proceeding in more lightly oiled areas. On sand and gravel shores, an asphalt pavement remained in a relatively sheltered area in 1993, but oil deposits had mainly broken up and disappeared from more exposed shores. The spill is described in many papers including [16][21][22].

Argo Merchant

The *Argo Merchant* ran aground on the Nantucket Shoals, off Massachusetts, USA, on 15th December, 1976, and over the next month spilled her entire cargo (28,000 tonnes) of heavy fuel oil and cutter stock. Storms broke up the tanker and attempts to pump the oil into another vessel failed. *In-situ* burning was tried on two occasions, but the slick failed to sustain a burn. There was no other significant attempt at clean-up at sea, due to strong wind and heavy wave action.

Winds during the spill were offshore and as a result no oil from the *Argo Merchant* ever reached the shoreline and no coastal impact occurred. The bulk of the spill formed large 'pancakes' and sheens on the surface which were carried away from the wreck site, out over the continental shelf and into the prevailing North Atlantic circulation pattern. The accident occurred at the time when the fewest potential effects on pelagic organisms would be expected; a period of low productivity in the water column, with few fish eggs and larvae present. Oiled birds were seen near the wreck but it was concluded that the spill probably had little effect on the coastal and marine bird populations off the New England coast. The spill is described in a number of publications, including [23][24][25][26].

Dona Marika

The *Dona Marika* grounded in Lindsway Bay near the mouth of Milford Haven on 5th August, 1973, and about 3,000 tonnes of petrol were spilled. Because the spill was in a semi-enclosed area and during a period of high winds and heavy seas, water-in-petrol emulsions were unusually formed and this retarded the evaporation rate. This spill therefore represents an extreme case of a toxic light product contacting marine flora and fauna. Sub-littoral effects included large numbers of narcotised bivalves and dead *Echinocardium,* and there were massive losses of invertebrates (notably limpets) from the rocky shores. This was followed by a spectacular proliferation of green algae, mainly *Enteromorpha.* Recovery (as assessed by a number of long-term monitoring transects within the area), was well-progressed by 1979. The spill is described in [15][27][28].

Amoco Cadiz

The *Amoco Cadiz* ran aground off the coast of Brittany on 16th March, 1978. Over a period of two weeks the entire cargo of 223,000 tonnes of light Iranian and Arabian crude oil and 4,000 tonnes of bunker fuel was released into heavy seas. Much of the oil quickly formed a viscous water-in-oil emulsion, increasing the volume of pollutant by up to four times. By the end of April oil and emulsion had contaminated 320 km of the Brittany coastline, and had extended as far as the Channel Islands.

Strong winds and heavy seas prevented an effective offshore recovery operation. In total, approximately 3,000 tonnes of dispersants were used [29], as well as some chalk sinking agent which transferred part of the problem to the sea bed. The at-sea response did little to reduce shoreline oiling. A wide variety of shore types was affected, including sandy beaches; cobble and shingle shores; rocks, seawalls and jetties; mudflats and saltmarshes. Removal of bulk free oil trapped against the shore using skimmers proved difficult, largely due to problems with seaweed and debris mixed with the oil. Greater success was achieved with vacuum trucks and agricultural vacuum units, although much of the free oil was simply removed by hand by more than 7,000 personnel (mainly military). A considerable portion of the oil that did come ashore eventually became buried in sediments and entrapped in the low energy salt marshes and estuaries.

At the time, the *Amoco Cadiz* incident resulted in the largest loss of marine life ever recorded after an oil spill. Mortalities of most animals occurred over the two-month period following the spill. Two weeks after the accident, millions of dead molluscs, sea urchins, and other benthic species washed ashore. Although echinoderm and small crustacean populations almost completely disappeared from some areas, populations of many species had recovered within a year. Diving birds constituted the majority of the nearly 20,000 dead birds that were recovered. Oyster cultivation in the estuaries (“Abers”) was seriously affected and an estimated 9,000 tonnes were destroyed because of contamination and to safeguard market confidence. Other shell and fin fisheries (including seaweed gathering) were seriously affected in the short-term, as was tourism. Clean-up activities on rocky shores, such as pressure-washing, as well as trampling and sediment removal on salt marshes caused habitat impact. Failure to remove oil from temporary oil collection pits on some soft sediment shorelines before inundation by the incoming tide also resulted in longer-term contamination.

Numerous clean-up and impact lessons were learned from the *Amoco Cadiz* incident, and it still remains one of the most comprehensively studied oil spills in history [26][29][30][31][32][33].

Tanio

On 7th March, 1980 the *Tanio* broke up during violent weather conditions off the northern coast of Brittany, France. As a result, approximately 14,500 tonnes of the heavy fuel oil cargo were spilled. Strong north-westerly winds moved the oil towards the same Breton coast which had been impacted by oil from the *Amoco Cadiz* almost exactly two years earlier, and from the *Torrey Canyon* in 1967. Due to the high viscosity of the oil and severe weather conditions, neither chemical dispersal nor containment and recovery techniques at sea were possible. Because of its persistent nature the spilled oil eventually contaminated about 200 km of coastline to varying degrees, with small amounts again spreading as far as the Channel Islands.

Bulk oil was removed from shorelines using tractor-drawn vacuum trucks, although this technique could not be used on cold, cloudy days when the oil became too viscous. The desire to speed up the removal of the bulk oil from priority amenity beaches in advance of a particularly high tide resulted in the use of bulldozers and front-end loaders. Whilst much oil (and a considerable amount of beach material) was removed within a short time, the underlying sediments at a number of sites were heavily contaminated and required extensive restoration work at a later stage. The removal of bulk oil was followed by the cleaning of the rocks in the tourist areas, using hot water washing machines and high pressure cold water jets, in time for the start of the holiday season in July.

Environmental and economic impacts were limited, although approximately 1,700 dead birds, primarily guillemots and other auks, were recovered during the incident. There were some localised fishery impacts, such as contaminated oyster beds and shellfish holding pens, as well as disruption of seaweed harvesting. Intertidal fauna and flora was also damaged by smothering and by the extensive clean-up operations at the severely affected areas. The lack of international media attention minimised the effect on tourism. The spill is described in [26][34][35].

Tropical spills - *Funiwa V* and Bahia Las Minas

The *Funiwa V* well, offshore Nigeria, blew out on 17th January, 1980. 20,000 tonnes of crude oil escaped, of which an unquantified but large amount went into the mangrove swamps of the Niger delta. At Bahia Las Minas, Panama, a storage tank ruptured at a coastal refinery on 27th April, 1986 and approximately 7,000 tonnes of mixed Venezuelan/Mexican crude oil entered nearshore waters including mangrove swamps. In both cases there were clean-up efforts (notably booming and recovery in Panama) but these were not possible over much of the dense, inaccessible mangrove forest.

These two spills have affected the greatest areas of mangroves to date and illustrate the particular sensitivity of this habitat. In the case of the Nigerian spill over 320 hectares (800 acres) of mangrove forest (including many large trees 10 or more metres in height) were killed [36], and in the case of the Panama spill [37] about 75 hectares (185 acres). In both cases the oiling of the mangrove habitat led to the death or tainting of molluscs (e.g. mangrove oysters) and crustaceans (e.g. crabs), some species of which are subsistence food items for local people. In the case of the Panama spill, oil leaching slowly from mangrove sediments was implicated in damage to adjacent sub-tidal corals [38]. Some coral reef-flat areas were also damaged by direct oiling at low tide. The response to the Panama spill was the largest mangrove re-planting scheme to date (with the aim of speeding up natural regeneration). It involved more than 86,000 mangrove seedlings which were planted out after one year. By this time, chemical monitoring and pilot transplant experiments had shown that the oil residues in the sediments had weathered and lost most of their toxicity to seedlings [39].

Castillo de Bellver

The *Castillo de Bellver*, carrying 252,000 tonnes of light crude oil (Murban and Upper Zakum), caught fire about 70 nautical miles north west of Cape Town, South Africa on 6th August, 1983. The blazing ship drifted towards shore and broke in two. The stern section - possibly with as much as 100,000 tonnes of oil remaining in her tanks - capsized and sank in deep water, 24 nautical miles off the coast. The bow section was towed away from the coast and eventually sunk with the use of controlled explosive charges. Approximately 50-60,000 tonnes is estimated to have spilled into the sea or was burned [40]. Although the oil initially drifted towards the coastline, a wind shift subsequently took it offshore, where it entered the north-west flowing Benguela current.

Although a considerable amount of oil entered the sea as a result of the *Castillo de Bellver* incident, there was little requirement for clean-up (there was some dispersant spraying) and environmental damage was minimal. The only visible damage was the oiling of some 1,500 gannets, most of which were collected from an island near the coast where they were gathering for the onset of the breeding season. A number of seals were observed surfacing in the vicinity of the dispersant spraying activities, but were not thought to have suffered any long-term effects. Also of initial concern was the black rain that fell during the first 24 hours on predominantly wheat growing and sheep grazing lands due west of the explosion, although no long-term damage was recorded from these residues. The impact on both the rich fishing grounds and the fish stocks of the area was also considered to be negligible. A brief summary of the incident is available in [40], with further details in [41].

Exxon Valdez

The *Exxon Valdez* grounded on Bligh Reef in Prince William Sound, Alaska, on 24th March, 1989. About 37,000 tonnes of Alaska North Slope crude escaped into the Sound and spread widely [42]. There was some limited dispersant spraying and an experimental *in situ* burn trial during the early stages of the spill but at-sea response concentrated on containment and recovery. Despite the utilisation of a massive number of vessels, booms and skimmers, only around 5% of the original spill volume was recovered from the sea surface. The oil subsequently affected a variety of shores, mainly rock and cobble, to varying degrees over an estimated 1,800 kms.

This spill attracted an enormous amount of media attention because it was the largest spill to date in U.S. waters (though well down the scale in world terms). Moreover, it happened in a splendidly scenic wilderness area with important fisheries and attractive wildlife such as sea otters and bald eagles. Consequently the response was the biggest and most expensive in oil spill history, with over 10,000 workers being employed at the height of the clean-up operations, many of them in shoreline clean-up, often in remote areas.

Shoreline clean-up techniques included high pressure hot water washing, which was carried out on a scale never attempted previously or subsequently. This seems to have delayed recovery of intertidal communities in some areas, although recovery on over 70% of oiled shorelines was progressing well in 1990. There were also some relatively large scale bioremediation trials that gave mixed results. About 1,000 sea otters are known to have died, and over 35,000 dead birds were retrieved. There were particular efforts to protect fisheries, for example with booming of salmon hatcheries. There is no good evidence of long-term damage to wildlife and fish populations.

Assessment of damage and recovery has been controversial because of the segregation of scientists into different camps, an unfortunate result of US litigation practices. The *Exxon Valdez* spill has generated a large number of scientific papers, key references (with different emphases, bearing in mind the controversy mentioned above) include [4][5][43][44].

Gulf War

In the final stages of the Gulf War during late January 1991, unprecedented amounts of oil (Kuwait crude) were released into the relatively confined waters of the Gulf. Estimates vary but the amount was probably in the order of 1,000,000 tonnes (hence its description as 'the mother of all oil spills' [45]. While hostilities continued, response efforts were concentrated on the protection of desalination plant and power station seawater intakes using protective booms and subsurface tarball nets. Attempts were made to recover oil floating on the Gulf but efforts were hindered both by familiar logistical problems, such as adverse weather, and the difficulties of operating in a war zone. Massive amounts of oil became trapped in a number of embayments. In the more accessible regions this was collected using skimmers, with the recovered oil pumped into temporary storage pits at the back of the beach. An overview of the response activities is given in [46].

A range of environmental remediation activities were carried out after the war, with most effort focused on particularly sensitive sites. For example, beaches on Karan Island were cleaned as a first priority activity because of their importance as a nesting site for green turtles [47]. High volume, low pressure flushing of free floating and pooled oil from mangroves was also carried out.

Survey results (including those obtained during the 100-day *Mt Mitchell* research cruise) show that damage was concentrated in the intertidal zone. Overall, damage to subtidal ecosystems such as coral reefs and seagrass beds was less than initially expected, probably partly because of the rapid stranding of large quantities of oil on the Saudi Arabian coastline. Heavy loading of some intertidal areas was associated with deep penetration into porous sand and into animal burrows in muddy sediments, and the subsequent formation of extensive asphalt pavements. These seal the subsurface oil from natural cleaning processes, and inhibit re-colonisation by flora (saltmarsh plants) and fauna. In the absence of clean-up beyond the removal of most bulk oil, it is estimated that contamination of some shores will remain for decades [48]. Information on all aspects of the pollution is available in [49].

Braer

The *Braer* ran aground in severe weather conditions on Garth's Ness, Shetland on 5th January, 1993 and over a period of 12 days the entire cargo of 84,700 tonnes of Norwegian Gullfaks crude oil, plus up to 1,500 tonnes of heavy bunker oil, was lost as almost constant gales broke the ship apart. Weather conditions prevented the use of mechanical recovery equipment at sea, although about 130 tonnes of chemical dispersant was applied from aircraft during periods when the wind abated slightly and some oil remained on the surface. Oiling of shorelines was temporary and clean-up involved the collection of oily debris and seaweed by a small workforce.

The *Braer* spill was very unusual in that a surface slick was not produced. A combination of the light nature of the oil and the exceptionally strong wind and wave energy naturally dispersed the oil through the water column. The oil droplets were adsorbed onto sediment particles which eventually sunk to the sea bed. Sub-surface currents led to this oil being spread over a very wide area, although a significant portion eventually ended up in two deep, fine mud sediment ‘sinks’. A wide range of fish and shellfish over a fairly large area became contaminated with oil, resulting in the imposition of a Fisheries Exclusion Zone. Farmed salmon held in sea cages in the surface waters within this zone bore the brunt of the contamination since they could not escape the cloud of dispersed oil. Although this contamination was lost quickly once clean water conditions returned, millions of salmon that could not be marketed had to be destroyed [18]. Although the Exclusion Zone was progressively lifted as fish and shellfish species were found by chemical analysis and taste testing to be free of contamination [17], it was still in place at the end of 1997 for a small *Nephrops* fishery in one of the fine mud areas.

The spill was unusual in that a significant amount of oil was blown on to land adjacent to the wreck site. The effects of this airborne oil were localised and had no more than a temporary effect on vegetation and sheep. Seabird casualties were also relatively low. Considering the size of the spill, the environmental impacts were surprisingly limited [50][51].

Nakhodka

On 2nd January, 1997 the *Nakhodka* broke up in heavy seas, about 55 nautical miles off the north coast of Japan, spilling some 6,000 tonnes of its fuel oil cargo. The stern section sank with an estimated 10,000 tonnes of cargo onboard, whereas the upturned bow section continued to drift towards the coast leaking oil at a slow rate. Five days later it stranded on rocks 200 metres from the shore, resulting in a substantial quantity of oil being released and causing heavy contamination of the adjacent coast.

A proportion of the oil that was lost when the ship broke up dispersed naturally at sea. Efforts to collect oil in the open sea were greatly hampered by severe winter weather and sea conditions, and by the wide distribution and fragmentation of the oil. As a result it proved impossible to prevent or reduce shoreline pollution to any significant extent and several hundreds of tonnes of highly persistent water-in-oil emulsion eventually stranded on the Japanese coastline at various locations over a distance of more than 1,000 km. The length of contamination was exceptional compared to the relatively small quantity of pollutant and this posed great problems for the authorities. Nevertheless, shoreline clean-up was effectively organised, primarily using manual methods. Around 10,000 people were involved, and most of the oil stranded on the shoreline was removed by mid-February.

Despite the wide geographical extent of the spill, the income of traditional fishermen was only marginally affected. The most important reason for this is the widespread practice of involving the fishing community in the nearshore and shoreline clean-up operation, thereby securing an alternative source of income during the critical period when fishing activity was prevented by the presence of drifting oil at sea. Seaweed gathering was severely disrupted because of oil contamination of intertidal rocks leading to the total loss of a year's harvest. Similarly, the whole stock of an onshore fish farm was lost following persistent oil contamination of sea water supplies.

Operators of a number of tourist resorts and a few bathing beaches along the oiled coastline are believed to have suffered economic loss. In particular, there are hot spring resorts with numerous restaurants and gift shops clustered around which are specifically geared to the tourist market. An account of some of the lessons learnt from this incident can be found in [52].

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