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REVIEW PAPER

The Threats from Oil Spills: Now, Then, and in the Future

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Abstract The ongoing oil spill from the blown-out well by the name of Macondo, drilled by the ill-fated rig Deepwater Horizon, has many features in common with another blowout in the Mexican Gulf that happened three decades ago. Then the oil gushed out from the Ixtoc I well drilled by the Sedco 135-F semi-submersible rig. In the years between these catastrophes, the source and nature of oil spills have undergone large changes. Huge spills from tankers that ran aground or collided used to be what caught the headlines and caused large ecological damage. The number and size of such accidental spills have decreased significantly. Instead, spills from ageing, ill-maintained or sabotaged pipelines have increased, and places like Arctic Russia, the Niger Delta, and the northwestern Amazon have become sites of reoccurring oil pollution. As for blowouts, there is no clear trend with regard to the number of incidences or amounts of spilled oil, but deepwater blowouts are much harder to cap and thus tend to go on longer and result in the release of larger quantities of oil. Also, oil exploration and extraction is moving into ever-deeper water and into stormier and icier seas, increasing potential risks. The risk for reoccurring spills like the two huge Mexican Gulf ones is eminent and must be reduced.

Keywords Oil spills · Blowouts · Deepwater Horizon · Ixtoc I · Marine environment · Pipelines · Tanker accidents

INTRODUCTION

An explosion on the BP-operated Deepwater Horizon oilrig in the Gulf of Mexico on April 20, 2010, has become the second-most publicized environmental catastrophe in decades. The only one that surpasses it as a media event is the Chernobyl nuclear meltdown. In making headlines, media has been helped by politicians, and since President Barack Obama early on upped the ante by talking about the ongoing oil spill as "potentially the worst environmental disaster in American history", the competition for media attention has prompted others, including representatives of environmental NGOs (non-governmental organizations), as well as some scientists, to come up with even more spectacular doomsday predictions—including devastation of the Atlantic and Arctic Oceans as well as Europe's west coast.

During the first month of the spill, scientists, authorities, politicians, and journalists alike, referred to the blowout as "unprecedented", and talked about damage "that will affect people on the coast for decades if not for generations".

The discovery of subsurface oil clouds were called "sensational" by some scientists, doubted by others, and outrightly denied by BP. The size of the spill was assessed by NOAA and BP using aerial and satellite images of surface oil coverage and darkness—a technique developed for surface spills of non-emulsified oil—with a severe underestimate as the result.

Yet, the Deepwater Horizon accident is not unprecedented. In 1979, a blowout at the Ixtoc I platform in the Bay of Campeche (Fig. 1) resulted in oil spouting into the water from the bottom of the sea. The spill went on for more than 9 months and, in total, close to half a million tons of oil (as estimated by Pemex, the state oil company of Mexico, which owned and operated the platform) were released, thereby making it the world's largest peacetime oil spill (Jernelöv and Lindén 1981a, 1981b). These two blowouts have a lot in common, not only with regard to the technical aspects involved but also to the characteristics of the oil. Many lessons from then seem highly relevant now. In all likelihood, many of the effects will also be similar.

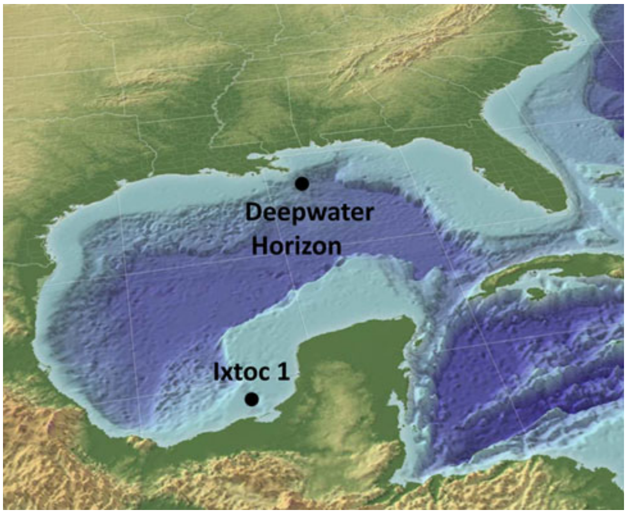

Fig. 1 The Gulf of Mexico in 3D perspective indicating the location of the two marine blowouts. *Source*: NOAA (http://oceanexplorer.noaa.gov/technology/tools/mapping/media/gis_gulf.html)

Despite the striking similarities between these two blowouts, the nature of oil spills in general has changed a lot during the decades between them. The oil extraction has also increased from under 3 million tons a day in 1960 to 10 million tons daily in 2005, where it has since remained (US Energy Information Administration 2009).

Before returning to these incidents, let's take a look at the trends with regard to different types of oil spills and to effects of oil in the marine environment and the effectiveness of countermeasures as that knowledge developed.

INTERNATIONAL OIL TANKER INCIDENTS

Decades ago, oil tanker accidents dominated the media picture of oil spills, and constituted a significant part of the human input of oil from sea-based activities. The number of such accidents has decreased significantly since the 1970s and the amount of oil that spilled even more so. The average yearly amount of oil entering the oceans from such sources was 314 000 tons in the 1970s, with no single year below 138 000. In the first decade of the third millennium, the average was 21 000 tons, with no year above 63 000 tons (Oil Tanker Spill Statistics 2009). The year 2009, even ended with the astonishingly low figure of 100 tons.

There are several reasons for this positive development. Modern tankers have double hulls, which lowers spill risk after minor impacts. Tankers are also sectioned, meaning that in case of leakage, the whole cargo is not lost. In addition, the establishment of sea lanes, with traffic moving in only one direction in narrow waters, such as the English Channel and the Malacca Straits, has reduced the number of collisions. Most important, however, the use of GPS (Global Positioning System) shows even the most inexperienced and possibly less-than-sober captain on duty during major holidays, where the ship is at any given time (all the more surprising, then, that a Chinese ship in January 2010 went far off course and hit the Great Barrier Reef).

However, accidents are not the only way tankers discharge oil into the marine environment—and are not even the most important when it comes to the quantities of oil discharged. Operational discharges, including tank washing with seawater, oil content in ballast water, and fuel-oil sludge spilled more oil than accidents did already in the 1970s. Although several steps have been taken to reduce these types of discharge, more substantial reductions have taken place, mainly in territorial and near-shore waters of the developed countries. For the period 1988–1997 the operational releases were estimated to be just over 200 000 tons per year. The development since then has led to a further reduction, but probably not more than 50%. The trend is clearly downwards, however, and is expected to continue.

Pipeline ruptures and leakages show the opposite trend. The number of marine spills (of over 0.17 tons each) has increased from an average of 47 per year in the decade from 1968–1977, to 188 ruptures and 228 leakages, respectively, in the following decades (GESAMP 2007). In the first decade of this millennium, some 350 pipeline spills have been reported. In the US, the number has quadrupled since the 1990s (U.S. Minerals Management Services 2010).

The reasons for this sharp increase are partly that the number and total length of oil pipelines have increased substantially since the 1970s, but two other factors are even more important. One is the ageing of pipelines and pumping stations. Especially in the former Soviet Union this is the cause of many leakages, and some of them are allowed to go on for years with the only remedial action being ditches and dams dug out to contain the oil. Also, in tropical West Africa, for example, age, sloppy maintenance, and corrosive conditions have led to many ruptures. Here, however, another factor also comes into play: pipelines become military targets in uprisings and tribal wars. The delta of the Niger River and parts of the Amazon are areas where intentional pipeline destruction regularly occurs.

MARINE BLOWOUTS

With regard to marine oil blowouts, it is more difficult to find a clear trend. Table 1 lists the largest spills, to which the Deepwater Horizon one will be added high up, possibly at the very top.

A more complete list does not change the impression that there was a relatively calm period from the late 1980s until the late 2000s, with larger losses before that period

Table 1 The largest marine oil blowouts hitherto

Well	Country	Year	Tons spilled	Comment
Ixtoc I	Mexico	1979	475 000	(Spill figure from PEMEX)
Nowruz	Iran	1983–85	100 000	(After attack by Iraqi airplanes)
Nowruz	Iran	1983	40 000	(After oil platform was hit by a tanker)
Ecofisk	Norway	1977	27 000	
Funiwa 5	Nigeria	1980	26 000	
Montara	Australia	2009	20 000	

and, lately, after it. In general, one can say that blowouts on land and in shallow water can mostly be capped relatively quickly, and that the resulting spills therefore seldom become very large. In deeper waters, blowouts are not very frequent, but when they happen, they often go on until relief wells can be drilled. This can easily take months, and the amounts of oil discharged can become enormous during this time.

The technologies for drilling for oil in deep water, and in the complex layers of sediments and rocks that lie beneath it, have improved tremendously in the last 30–40 years. They now have an aura of space technology about them. Even safety measures such as blowout preventers are now much more advanced than they were. However, as oil companies move to more and more difficult places in their hunt for oil, the challenges have also grown, and have perhaps done so even faster than the technology and technical capabilities.

CATASTROPHIC OIL SPILLS

Returning to the days of spectacular and catastrophic tanker accidents and huge oil spills (Table 2 lists the largest), a number of lessons about the effects of oil and methods for handling the spills were learned, but appear to have been half-forgotten since.

The first really big oil spill from an early super tanker was that from the Torrey Canyon in 1967 on the Isles of Scilly of Cornwall. There was no experience of large-scale oil spills at the time, and the attempted countermeasures were to a large extent improvised. In an attempt to burn the oil, British military aircraft bombed the wreck and the oil on the surface with napalm. What was the result of this? Very little oil burned. Oil on the sea surface is cooled by the water underneath, and burns badly. When the oil becomes emulsified, with water droplets in it, it hardly burns at all. When, in addition the oil becomes somewhat "weathered", meaning that much of the volatile fractions have evaporated, more inflammable material, like napalm, has to be added than the amount of oil that actually will burn. A total of 10 000 tons of dispersants were sprayed at the oil, both at sea and on beaches, and found to be both toxic in themselves and to render the oil more toxic, thus exacerbating rather than alleviating the damage to aquatic life.

After the Torrey Canyon spill there was no quantification with regard to the damage done on populations of fishes, crustaceans, and molluscs, but the overall effect on fisheries was seen as mild (Simpson 1968). Some 15 000 bird succumbed, and those subjected to washing attempts had insignificantly higher survival rates than those that

Table 2 The largest oil spills from tankers (Oil Tanker Spill Statistics 2009)

Position	Ship name	Year	Location	Spill size (tons)
1	*Atlantic Empress*	1979	Off Tobago, West Indies	287 000
2	*ABT Summer*	1991	700 nautical miles off Angola	260 000
3	*Castillo de Bellver*	1983	Off Saldanha Bay, South Africa	252 000
4	*Amoco Cadiz*	1978	Off Brittany, France	223 000
5	*Haven*	1991	Genoa, Italy	144 000
6	*Odyssey*	1988	700 nautical miles off Nova Scotia, Canada	132 000
7	*Torrey Canyon*	1967	Isles of Scilly, UK	119 000
8	*Sea Star*	1972	Gulf of Oman	115 000
9	*Irenes Serenade*	1980	Navarino Bay, Greece	100 000
10	*Urquiola*	1976	A Coruña, Spain	100 000
11	*Hawaiian Patriot*	1977	300 nautical miles off Honolulu	95 000
12	*Independenta*	1979	Bosphorus, Turkey	95 000
13	*Jakob Maersk*	1975	Oporto, Portugal	88 000
14	*Braer*	1993	Shetland Islands, UK	85 000
15	*Khark 5*	1989	120 nautical miles off Atlantic coast of Morocco	80 000

went untreated. Hundreds of kilometers of beaches in both England and France were coated with oil.

ENVIRONMENTAL EFFECTS AND REMEDIATION

Many oil spills later, and after some systematic studies of the effects of oil and the effectiveness of techniques to combat oil spills (most notably the long-term project conducted at the Water and Air Pollution Research Institute (IVL) with funding from the Swedish Coast Guard and the Petroleum Institute), a fairly clear picture had emerged (GESAMP 1977; Jernelöv et al. 1975).

Oil spilled on water spreads out in a relatively thin layer on the surface. Lighter components gradually evaporate, and some water-soluble ones dissolve. Wave action will break up the oil, creating oil droplets in the water and water droplets in the oil. The oil thereby changes into an emulsion, brownish in color, and often referred to as "chocolate mousse". As more and more water gets into the oil emulsion it reaches a point where the water dominates and the emulsion changes to one of oil droplets in water, much as in an oil-and-vinegar salad dressing.

As long as the oil is on the surface, UV radiation from sunlight will help to break down the oil components, specific bacteria will attack the droplets suspended in the water, and biodegradable components will thus be consumed.

Some fractions of the oil are fairly persistent and, e.g., a group called asphaltens will resist both photo- and biochemical degradation for a long time. These asphaltens will accumulate in sediments and on beaches, but are more or less inert.

Dependent on the composition of the oil (for instance, if it is a light or a heavy crude, or a refined product such as diesel) the proportion that undergoes these different phases varies greatly. Likewise, temperature, light intensity, and water turbulence will be important for both the speed of the processes and the end results. Dispersants will speed up the emulsification process.

With regard to effects, oil on the surface can smother seabirds and be washed up onto beaches. The birds are also susceptible to small oil spots, as oil on their feathers impairs their normal insulation and leads to hypothermia. On beaches and in inter-tidal zones, the oil may smear and poison the organisms that live there, and will also impede bathers and tourists.

Oil droplets in water will act as flypaper for a large number of small creatures, and entrap and kill them. Larger ones may ingest the oil when they go for their trapped-food sources, or they may inhale it and get it stuck on their gill membranes as they swim through the emulsion. If they get exposed to high enough concentrations, they will die; at much lower levels of contamination, they will become impaired and tainted.

Thus, to disperse the oil may help protect birds and beaches, but it will increase the exposure of fishes, crustaceans, molluscs, and all other organisms that live and breath in water.

ANOTHER OIL SPILL EFFECT

As more and more follow-up studies after massive oil spills were reported, another effect was noticed. On many rocky shores and in shallow waters, massive amounts of green algae were found, often months or even years after the spills, e.g., in the aftermath of the Torrey Canyon incident. The reason for this was misunderstood in many of the early reports, as the phenomena resembled that of excessive nutrient load, man-made, or as the result of a large colony of seabirds. Thus, it was often assumed that nutrients had been set free through the bio- or photochemical degradation of oil.

The explanation turned out to be a quite different one. Oil poisoned snails and other algae grazers. With them out of the way, the green algae had a period of unimpeded growth. When the grazers returned, which in the case of snails after a massive oil spill might take a while, the mats of algae were so thick and wide that it took a long time for the original balance to re-establish. Many organisms, like mussels with plankton larvae, had difficulty in re-settling as the algae now occupied the space (Peterson et al. 2003).

As oil contaminated birds are easy to spot and count relative to other organisms affected by the oil, and as they provide good, dramatic illustrations of the catastrophic impact of spilled oil, there was a tendency in the late 1960s and early 1970s to use the number of birds that succumbed as a shortcut to impact assessment. The limitations and the one-dimensional character of that approach, however, were clearly demonstrated by an episode that took place in the Baltic just east of the island of Öland in February 1976. On a windy day, a passing oil tanker that had unloaded its cargo in a nearby port washed its tanks with seawater and released a relatively small amount of oil, some five tons. The oil had the effect of calming the waves, and the relatively flat water at the spill site attracted a large flock of long-tailed ducks, *Clangula hyemalis*, that happened to be flying by, with the result that around 60 000 of them perished (Wennergren et al. 1976). No other effects were documented. This episode also brought home the message that the effects of an oil spill are far from dependent solely on the quantity and type of oil. The time and place are also decisive.

SCIENTIFIC STUDIES AND FRUSTRATIONS

By 1976 the above-mentioned group at IVL, which had been studying the effects of oil spills in different aquatic environments and the effectiveness of oil spill combat and clean-up techniques, had already taken the first steps to becoming an expert body that UN organizations often called into assess oil spills. From the early 1970s to the early 1990s, members of the group advised on clean up and assessed damage in some 40 oil spill cases, mostly in developing countries, including the two largest ones: the Ixtoc blowout in 1979 and the Gulf War in 1991. These missions, organized through FAO (Food and Agriculture Organization of the United Nations), IMO (International Maritime Organization), IOC (Intergovernmental Oceanographic Commission), UNEP (United Nations Environment Program) or WHO (World Health Organization) at the request of the governments in the affected countries, provided excellent opportunities for conducting interesting studies. For the participating scientists, they also had frustrating aspects. One being that the reports they wrote could only be made public after clearance by the involved government(s). Far too often, that clearance was not forthcoming and the reports were instead suppressed. As a result, the scientists had to wait some years and then write about the episodes in the form of overviews or popular-science articles, in which they could only use information that was available from other sources. Their intimate knowledge about the cases obviously helped them to select the material they used, so that the resulting picture became close to the one they themselves had acquired at the time and on the spot. However, the open sources had occasionally missed important elements or had used figures provided by the oil companies or tanker owners without questioning them. Many times it was a balancing act to find the right wording, while at other times they had, reluctantly, to conclude that they simply couldn't find enough relevant material and reliable data from open sources to write a worthwhile piece.

OIL SPILL EFFECTS ON VULNERABLE SPECIES

Generally speaking, the immediate toxicity of oil is higher in warmer waters, but weathering and biodegradation are also faster, and so is the rate of recovery of damaged populations. The old chemical and biochemical q-10 rule—the speed of processes doubles for every 10 °C increase in temperature—is no bad rule of thumb also in this respect. When studying oil spill effects in tropical and subtropical waters, however, there were types of short-term effects that led to long-term damage that had not been seen in cold or temperate waters.

One of these effects relates to corals. The small animals that build the coral reefs are sensitive to oil components and are often killed when oil spills occur near the reefs. Horn corals are among the most susceptible species. When ocean swells break against barrier reefs, branches of dead corals are broken off in the turbulence, and sometimes large sections of the upper parts of reefs can disappear in this way. As a consequence, erosion of beaches can increase substantially behind the damaged barrier reef. In extreme cases, if the land behind the reef is composed of a small sandy island, large parts or even all of it can erode away. Once the reef is re-established the island may reform, but that is a long-term process (Jernelöv et al. 1975).

Another short-term effect with long-term consequences relates to mangroves. They often grow in muddy areas in the mouths of rivers, and the mud, rich in organic material, is often anaerobic. For the roots to survive, they often have pneumatophores, a type of tube that grows vertically from the horizontal roots, and ends a decimeter or two above the sediment. They look like chimneys, but actually serve to aerate the root system. If they become clogged by oil, the mangroves may die. As the mangrove root systems help stabilize the mud they live in, after their death the mud they held is often flushed out into the sea, making re-colonization a very slow process (Jernelöv et al. 1976; Jernelöv and Lindén 1981b).

Another similar process, in which oil toxicity can kill off a group of organisms and may lead to a change in the physical structure, has been suggested with regard to tube-building polychaete worms. Their tubes stabilize sediments (Fager 1964) in the same way plant roots do. When the animals die and the tubes degrade, the sediments could become more exposed to erosion, and even lead to underwater landslides. Other authors, however, point out that polychaetes belong to the most oil-tolerant groups in the benthic fauna (Dutriex et al. 1989).

The Exxon Valdez oil spill in Alaska in 1989 led to some new observations and experiences. With regard to effects, it was estimated that the oil killed over a thousand sea otters, *Enhydra lutris*, as well as some 300 harbor seals, *Phoca vutulina*. The mechanism through which oil damaged the sea otters is easy to understand and is much like the way birds are impacted. Oil on the fur reduces its insulating capacity, and the animals die from hypothermia. This could also be a factor of importance for fur seals, but for other smooth-skinned seals the mechanism that causes mortality is less clear. Harbor seals are insulated by subcutaneous fat, and oil would not interfere with that. Eyes, nose, ears, and throat would certainly be irritated by oil, but is it enough to kill a seal? Inhalation of volatile components of the oil could likewise irritate, but again, would it kill? The answer may well be that a combination of irritation and perhaps dislocation causes stress that in some cases becomes fatal. One reason to dwell on the question of the cause of death is that acute seal mortality has not been reported from many other areas like the North Sea and the Strait of Magellan, where seal populations have been hit by oil spills. Often, but not always, seals have been seen to avoid the oil (Geraci and St. Aubins 1990). Naturally, seal puppies or moulting seals are more likely to be in danger.

Another group of marine animals of concern with regard to oil spills is sea turtles. There are many reports of findings of dead turtles in connection with oil spills, but sometimes more in the vicinity of the spill than directly in the middle of it. In connection with any media-covered spill in waters where sea turtles live, damage to these endangered species comes high on the list of fears that environmental experts and activists alike express. Hard facts about mortality are more rare. The findings in connection with oil spills do not necessarily have to reflect a higher mortality rate, it could also be a consequence of more careful observations and systematic reporting during spill episodes. As with seals, the question is also what the mechanism of toxicity would be and the possible answers might be the same: irritation of, e.g., eyes and nose, inhalation of fumes, etc. Again, as with seals, the question arises if that would be enough to kill them. Freshwater turtles exposed to oil in similar ways have not readily succumbed. It has been proposed that sea turtles might ingest large quantities of oil if they mistake the brownish oil emulsified with water droplets called "chocolate mousse" for decomposing seaweed, but that possibility still needs to be verified. What is clear, however, is that eggs and hatchlings can suffocate if the beach becomes oil covered and that this could wipe out much of a year class of a species with few spawning places. As a precaution, at the time of the Ixtoc oil spill, some 9000 newly hatched Kemp Ridley Turtles, *Lepidochelys kempii*, were transported out to oil-free sea and a few thousand turtle eggs were moved from Mexican beaches threatened by oil to safer havens in the USA and on Cuba.

BIOREMEDIATION

The Exxon Valdez spill also saw the first large-scale application of bioremediation enhancement agents. Although some degree of success was later reported, doubts were also expressed with regard to their effectiveness.

An observation of principle interest, which agrees with recovery findings following other types of pollution, was that the ecosystems of the Prince William Sound experienced prolonged periods of unusual fluctuations caused by indirect interactions such as trophic cascades, in which predators reduce abundance of their prey, which in turn releases the prey's food species from control, as well as provision of biogenic habitat by organisms that serve as or create important physical structure in the environment (Peterson et al. 2003).

Also, in some other aspects, the Exxon Valdez accident provided some new perspectives on oil spills. The media attention was, at the time and until the current Deepwater Horizon blowout, unmatched. This made many people believe that it was the largest oil spill ever. As can be seen in Table 2 above, it didn't even make it among the top 15 tanker spills. In fact, it ranks as number 35 (Oil Tanker Spill Statistics 2009). Another new feature was that reported casualty figures were no longer just the numbers of, e.g. dead birds found—some 60 000—but also an "estimated" 3–4 times higher number. A third aspect was the intensive clean-up attempts and the associated costs of $2.2 billion, which were unmatched at the time. In addition, Exxon Mobile paid $1 billion in settlements with the State of Alaska and the federal government—also that was unprecedented at the time.

LEAKING PIPELINES AND OIL SPILLS

Returning to leaking pipelines and the oil spills associated with them, the number of such incidents that are officially reported and that lead to spills in marine environments has increased substantially over the latest four decades. However, the largest and most substantial spills are not included in these statistics. For example, in the Niger Delta, the Russian Arctic, and in the northwestern Amazon, very substantial amounts of oil are spilled with disturbing regularity, but are seldom reported and rarely cleaned up. True enough, only smaller parts of this oil reach the sea, but that does not mean that the effects are not devastating. Oil on agricultural land, in forests and delta-arms with fresh or brackish water, on Arctic tundra, or in rainforests, is in no way benign.

Niger Delta Oil Spills

In the Niger Delta, according to a report by WWF, the IUCN, representatives from the Federal Ministry of Abuja, and the Nigeria Conservation Foundation in 2006, a total of 1.5 million tons of oil have been spilled in the delta over a 50-year period (Obot et al. 2006). Amnesty International has also presented similar figures (Gaughran 2009). The Nigerian federal government says that there were more than 7000 spills between 1970 and 2000, and there are 2000 official major spillage sites, many going back over decades, as well as thousands of smaller ones.

The delta landscape is criss-crossed with pipelines and punctuated with pumping stations that connect the over 600 oilfields with storage facilities and tanker loading ports. Often these installations and the spills are in close proximity to villages. The oil spills contaminate agricultural fields as well as fishing areas and drinking-water sources, and often the poor farmers and fishermen have to eat contaminated food and drink oily water. The ecological effects have only been spot-wise investigated, but those few studies and the preponderance of oil on land and water make it obvious that the impact is massive.

There are several causes of the spills. Rust and lack of maintenance, together with waste dumping, are causes that clearly lie within the responsibility of the companies involved. The companies, with Shell at the forefront, but also including Total, Mobil, Chevron, Elf, and Agip, claim that such spills are minor only, and that vandalism, theft, and sabotage by militants are the causes of most spills. Local environmental and human rights NGOs contest these claims.

Hitherto, international oil companies have enjoyed a cozy relationship with their partner, the Nigerian National Petroleum Corporation (NNPC) and with the Nigerian government, whose coffers they fill. That coziness may be changing with the recent establishment of the National Oil Spill Detection and Response Agency (NOSDRA). However, there is a very long way to go to free the people and the environment of the Niger Delta from the menace of oil pollution.

Arctic Oil Spills

There are many rumors and tales and even media reports about oil spills from pipelines in the former Soviet Union, but few have been well investigated, studied, and/or reported. One event was the spill in 1994 near the town of Usinsk, just south of the Arctic Circle. A pipeline had been leaking for more than half a year and the spill had been handled in the usual way: ditches had been dug and a dam built to collect and contain the oil. After heavy rains in October of that year the dam burst, and a total of over 100 000 tons of oil spread over the tundra and into the Pechora River. Clean-up operations over autumn and early winter were hampered by the lack of equipment, and collected only some 6000 tons of oil. A new leak spilled another undisclosed amount of oil, which covered a frozen area of 350 ha. The clean-up crew tried to handle this spill by setting fire to the oil. A lot of smoke was generated, but it is unclear how much of the oil was actually burned. As spring came, it was obvious that the combination of oil and fire after the second discharge had damaged the lichens, mosses, and scrubs of the tundra even more than the oil from the first discharge.

Over the winter season, the oil from the dam burst had been covered with snow, but it was clear that with snow melt and the spring flood, much of it risked being flushed into the Pechora River and into the Arctic Ocean. In an unusual move, triggered by the rare international publicity this particular spill had received thanks to Greenpeace (Horsman 1995), the Russian authorities requested and received a $99 million loan from the World Bank to pay for the further clean up of the Usinsk spill. Now, equipment and more manpower could be brought in. However, by that time it was already late April, and the spring flood was on its way.

With the melt of the snow that had been on top of the oil, spread out over some 200 km^2 of the flat landscape of tundra and marshes, the black oil and the many hours of daylight combined to warm up and thaw the underlying frozen layers more quickly and to a deeper level than normal. Thus, the oil created its own carrier water, and when it moved and was stranded somewhere else, the story repeated itself until it reached the rivers; first the Kolva and the Usa, and then the Pechora. However, from there it did not flow straight to the Arctic Ocean. As these rivers flow north, the spring flood starts in the upper parts of the rivers while the lower regions are still frozen. Thus, the flood water is again forced out over the landscape, before it hits the ice barriers, carrying much of the oil with it, and the process then goes through another cycle.

When the oil finally reached the sea, around midsummer, it had weathered in a peculiar way. Photochemical breakdown had progressed relatively far, thanks to the many hours of light and the thin layers in which it had been spread out. Biochemical breakdown had barely started because of the low temperatures, and the freshwater droplets that had emulgated in the oil, mostly during passage through somewhat turbulent river sections, were frozen to ice crystals in the subzero temperatures of the brackish Arctic Ocean surface water. Much of the oil looked like the feces of the local geese, but many of them were still smeared by it. The number of birds affected could not be assessed. Likewise, several thousand migrant mallard ducks, *Anas platyrhynchos*, were reported to have landed in an oil-contaminated shallow lake in the marshlands near Usinsk, but the casualties remain unknown. Better documented is the thermo-cast erosion of the tundra following the oil coverage and the vegetation kill off (Bazilescu and Lyhus 1996).

In the course of the investigations of the 1994 Usinsk oil spill, several earlier large spills in the area were also disclosed, such as a 1988 pipeline burst and a fire leading to the spill of 20 000 tons of oil, and in two incidents in 1992, close to 30 000 tons of oil leaked from ruptured pipelines.

Northwestern Amazon Oil Spills

In the Ecuadorian, Peruvian, and Columbian part of the Amazon spills of oil, drilling mud and other toxic components associated with the exploration and exploitation of oil and gas have polluted large areas of rainforests, including streams and rivers. Much like in Nigeria, it has also made the indigenous population (who bear the brunt of the burden of pollution and receive very little if anything at all of the economic benefits) protest, sometimes violently, against the foreign oil companies and their own central governments and occasionally also even sabotage the installations themselves.

The cases in Ecuador and Peru are strikingly similar on the surface. A US oil company, Occidental in Peru and Texaco (now a part of Chevron) in Ecuador, started prospecting for oil in the 1960s and 1970s and continued with extraction when oil was discovered. During operations they released huge quantities of toxic waste, euphemistically called "produced waters", into streams and onto lands in the Amazon rainforest. They also routinely used unlined and uncovered earthen ponds, which often overflowed, to store toxic chemicals. Both of these practices were banned in the USA, but according to the companies, were permitted in Ecuador and Peru. Environmentalists and lawyers representing indigenous peoples, for their part, claim that these practices, although not explicitly forbidden in themselves, were covered by a general ban on practices that are harmful to the health of people. The companies are also accused of having caused numerous oil spills through inadequate infrastructure and sloppy maintenance. When legal processes and challenges became prevalent in the 1990s, the US companies pulled out, leaving an environmental mess behind, or as they see it, in the hands of the Latin America-based operators that had taken over, if not in those of the host governments. Since then, complex legal procedures involving legislation in different countries with lawsuits and counter-suits have been ongoing and are now well into their second decade. In the meantime, the new operators seem to have continued many of the bad practices introduced by their US predecessors.

The case of Colombia is somewhat different with regard to the background and cause of the problems, if not to the resulting environmental and health situation. Also here, Occidental is a major actor, but the focus of the dispute is not so much on the way they extract the oil and handle the waste, but on a pipeline built in 1986 to transport the oil from the fields to the Caribbean coast. The 780-km-long pipeline, called Caño Limón, has been the target of both the FARC and ELN guerrillas. It has been attacked more than a thousand times and Occidental has been paying both the Colombian government and the guerrilla groups themselves for protection, as the company's vice president Lawrence Meriage testified in the U.S. Congress (Le Billon 2005). The total volume of oil spilled from the pipeline over the years is estimated to be some 400 000 tons.

These are mere examples of the environmental legacies of oil companies operating in the Amazon region. Reports of renewed and new leakages from pipelines and production sites are common, yet most spills remain unreported.

As the resistance of indigenous people to continued and new oil exploration increases, violent clashes between local Indian activists and the security guards of the oil companies or the military become more common and the sabotage of installations has become a weapon. Unperturbed by historical environmental experience or growing resentment by the local population, president Alan Garcia in Peru has been pushing for more than the already allocated 70% of the Peruvian Amazon to be opened up to foreign oil companies.

CALCULATING THE SIZE OF OIL SPILLS

While the opposite trends with regard to tanker spills and pipeline ruptures are clear, oil discharges from blowouts show no clear temporal pattern. Not only are the long-lasting, and thereby really large discharges rare, it is also difficult to calculate how much oil has really been spilled.

Probably the largest amount of oil emanating from a blowout gushed out of Lakeway no. 1 in San Joaquin Valley in California over a period of 18 months, 100 years ago, from March 1910 to September 1911. According to the San Joaquin Geological Society (2002), an estimated 1300 000 tons of oil sprouted out, of which only a smaller part was collected and piped to the coast, but this sufficed to send world oil prices plummeting.

From Baku and the Caspian Sea, where the Nobel Brothers Petroleum Company extracted oil from 1874 until the Russian Revolution, being at the time the dominating European oil company and the second worldwide after Rockefeller's Standard Oil, there are many rumors of long-lasting blowouts, but no one seems to have bothered to try to quantify them.

That brings us to 1979 and the Ixtoc blowout, which lasted for more than 9 months (Fig. 2). The spill figure that has made it into all databases and reports is the Pemex figure of 475 000 tons. The company had no better techniques then than those available to BP and the US authorities today to estimate the oil flow. As operators, they had all the reasons in the world not to overstate the release figures. Pemex tried the very same methods then that BP has now been using to cap the well and to reduce the flow, and they called in the hotshots of the oil blowout business then, like Red Adair, to help. These experts came and went, and the contractors as well as Pemex, the operator, had the same desire to report at least a partial success, so discharge figures were stepwise adjusted downwards. The UN advice and assessment team could not always see whether the flow

Fig. 2 Ixtoc I, 1979. The booms were not very effective. Oil is shown on both sides of the boom (photograph by Olof Lindén)

had actually decreased, when such progress was reported. In the end, we were quite sure that the size of the spill was underreported, but we had little or no basis for a specifically higher figure (as our report never received the clearance from the Mexican government it needed to be published in full, in the end it did not matter).

THE CASE OF DEEPWATER HORIZON, GULF OF MEXICO

In the Deepwater Horizon case, BP and US authorities initially reported a spill of approximately 800 tons a day. It was quickly pointed out that the technique used—aerial and satellite images—was inadequate for a blowout from the bottom of the ocean and led to an underestimation.

Subsequently, after BP released video pictures of the fountains of oil sprouting from the bottom into the water together with information of pipe diameter, independent experts were able to make more precise calculations and came up with much higher figures than the official ones (Fig. 3). Even if there was a practically unison agreement that the 800 tons a day was a severe understatement, there were huge discrepancies as to how much higher the true figures could be. In order to resolve the question of the size of the spill, Admiral Thad Allen, the National Incident Commander, appointed the Flow Rate Technical Group under the chairmanship of Dr. Marcia McNutt. For their first assessment, they used three independent methods and on May 27, 2010, they issued their first preliminary report.

The conclusion of the report was that the only range of flows that was consistent with all three methods used by FRTG was 12 000–19 000 barrels per day, corresponding to 1600–2600 tons. In order to illustrate the intricacies of flow-rate calculations from marine blowouts and thereby the uncertainties associated with other figures derived from more back-of-the-envelope-like estimates, an excerpt from that first report from the group is given below. It is to be further noted that the group to a significant degree has subsequently revised its initial assessment.

Fig. 3 Main oil leak at end of riser pipe/12 in. Wrench and ROV in background. © BP p.l.c

> The first approach led by the Mass Balance Team analyzed how much oil was on the surface of the Gulf of Mexico. The Mass Balance Team developed a range of values using USGS and NOAA analysis of data that was collected from NASA's Airborne Visible Infrared Imaging Spectrometer (AVIRIS), an advanced imaging tool. Based on observations from May 17, 2010, and accounting for thin oil not sensed by the AVIRIS sensor, the FRTG estimated that between 130 000 and 270 000 barrels of oil were on the surface of the Gulf of Mexico. It is important to note that the FRTG also estimated that a similar volume of oil to the amount AVIRIS found on the surface has already been burned, skimmed, or dispersed by responders or has evaporated naturally as of May 17. Given the amount of oil observed and the adjusted calculations for the amount of oil that has been burned, skimmed, dispersed, or evaporated, the initial estimate from the Mass Balance Team is in the range of 12 000–19 000 barrels of oil per day. This methodology carried several challenges, including the fact that the AVIRIS plane can only fly over a portion of the spill in a day, meaning that an assumption must be made that the area imaged is representative of the entire spill region.
>
> The second approach, which was led by the Plume Modelling Team, used video observations of the oil/gas mixture escaping from the kinks in the riser and at the end of the riser pipe in addition to advanced image

analysis to estimate fluid velocity and flow-volume rates. Based on advanced image analysis and video observations, the Plume Modelling Team has provided an initial lower bound estimate of 12 000–25 000 barrels of oil per day. They continue to work to provide an upper bound. This team faced several methodological challenges, including having a limited window of data in time to choose from, getting good lighting and unobstructed views of the end of the riser, and estimating how much of that flow is oil, gas, hydrates, and water.

Both estimates from the Mass Balance Team and the Plume Modelling Team were reality-checked with a basic calculation of the lower limit of possible oil that is spilling. The lower limit was calculated based on the amount of oil collected by the Riser Insertion Tube Tool (RITT), plus the estimate of how much oil is escaping the RITT, and how much oil is leaking from the kink in the riser. On May 25, 2010, at approximately 17:30 CDT, the RITT logged oil collection at a rate of 8000 barrels of oil per day, as measured by a meter whose calibration was verified by a third party. Based on observations of the riser, the team estimated that at least 10% of the flow was not being captured by the riser at the time oil collection was logged, increasing the estimate of total flow to 8800 barrels of oil per day. Factoring in the flow from the kink in the riser, the RITT Team calculated that the lower bound estimate of the total oil flow was at least 11 000 barrels of oil per day, depending on whether the flow through the kink is primarily gas or oil. The lower bound estimate calculated by the RITT Team is more than twice the amount of the earlier flux estimate of 5000 barrels of oil per day and is independent of any calculations or model assumptions made by either of the teams above.

The latest figures available at the time of writing (end of June, 2010) give a span of 4000–4800 tons per day before the riser was cut. Thereafter, the flow increased, according to these calculations, to somewhere in the range of 5600–9500 tons, of which a proportion—less than half—could be captured and pumped to processing and temporary storage in tankers on the surface. This would mean that the total spill at the end of June had reached 250 000–400 000 tons and was ongoing (Fig. 4).

Fig. 4 Oil on the surface of the water in the Gulf of Mexico May 17, 2010. © BP p.l.c

LARGEST OIL SPILL EVER IN COMPARISON

The largest oil spill in all categories, however, was a war-related incident. During the Gulf War, in Kuwait in 1991, in anticipation of a landing by the US Marines from the sea, much like D-Day during World War II, the Iraqis emptied all the oil-storage tanks along the coast, the strategy being to set fire to the oil when the enemy came, roasting them in the flames. The enemy didn't come, not that way, and the war took a totally different turn. Left in the Persian Gulf was 1200 000 tons of intentionally discharged oil (Fig. 5). The contamination was, obviously, massive but the damage, as far as it could be assessed under the circumstances, only moderate (Lindén and Jernelöv 1999). Even local coral reefs, sometimes referred to as 'seasonal' as they appear dormant during the part of the year with highest temperature and salinity, were not severely affected, perhaps because they were hit during their inactive period. Evaporation of volatile oil fractions, photo-oxidation, and general weathering progressed rapidly at the high temperatures and in the calm shallow waters of the Gulf.

Shrimp populations were damaged, but also benefited from the reduced fishing pressure during the occupation, the war, and the time directly afterwards. A few years later, it was "better than anyone could remember that it had ever been", as a local fisherman put it. Landing statistics supported his view, but new boats and equipment may have helped, too.

OIL SEEPAGE

As difficult as it is to assess the flow rate of an ocean-floor blowout, it is still child's play compared to estimating the natural seepage of oil into the ocean. Seepage occurs at thousands, if not more, different places. Mostly the general area rather than the specific site of the seep is known. Given this, and the fact that the difficulties in assessing release rates at any specific site are no smaller than for assessing flow rates from a blowout, one can find it self-evident that so few attempts have been made to assess the global natural oil seepage to the oceans. On the other hand, given the significance (also in PR terms in cases of accidents), one may find it surprising. Regardless, what remains is that few assessment attempts have been made, and the ones widely referred to are by the US National Academy of Sciences.

Fig. 5 Oil on the Persian Gulf during the 1991 Gulf War. A very thick layer of oil on the sea and part of the beaches formed as a smooth, black surface reaching as far as the eye could see. Smoke from the burning oil wells (not visible in photo) reduced visibility region-wide

In 1975, a "most likely" figure of 600 000 tons annually within a wide range (200 000–6000 000) was suggested (Wilson et al. 1974). In 1985, the figures were revised to between 20 000 and 2000 000 tons per year, with a "best estimate" of 200 000. No actual new data were presented to support this revision; based on the argument that the figure couldn't be as high as previously assumed, because the underwater oil wells would then have been naturally depleted over geological times and would not exist today. Thus, the argument went, the seepage rate must be much lower (Kvenvolden and Harbaugh 1983). In 2003, the figure was adjusted back to the level of 600 000 tons. New technologies, especially in the field of remote sensing, have been developed and applied to seepage studies. Using these on US waters, natural oil seepage in the American part of the Gulf of Mexico was calculated to be 70 000 tons annually and double that in the whole area (Mitchell et al. 1999), while the rates in offshore California and Alaska were 20 000 tons each per year. Thus, it was unlikely that the global figure would be just marginally higher than that for those three areas, and the first higher figure of 600 000 tons was resurrected (Keith et al. 2002).

This obviously is an area where uncertainties are huge and where better figures would be welcome. It is worth noting, however, that the effects of oil slowly and semi-regularly flowing into the sea are far less dramatic than when the same quantity comes from an oil spill.

THE IXTOC I AND DEEPWATER HORIZON COMPARED

Returning to oil spills from blowouts in the Gulf of Mexico and the two strikingly similar events 31 years apart, the Ixtoc I and the Deepwater Horizon accidents, the first thing to note is how all but forgotten the first episode had become when the second one happened.

One of the things noted in the Ixtoc case (and highlighted in reports) was the behavior of the oil when injected and mixed with gas under high pressure into the seawater at the sea floor. In this situation, a three-phase emulsion with oil, gas, and water was formed also containing sand and mineral particles. Such a mixture can have different densities dependent on the exact composition, and the density also varies over time as the composition changes. Thus, it can form underwater clouds that ride on density gradients. In the Ixtoc case, surveillance aircrafts of the US Coast Guard didn't see any approaching oil and yet it was suddenly there on the beaches.

Yet, when in the Deepwater Horizon case scientists reported that they had found extensive underwater clouds of oil, they themselves described it as "sensational" and "totally unexpected". Other scientists and US governmental agencies doubted the observations and asked for verification and BP outright denied that there was any oil under the surface.

The similarities between the two major Mexican Gulf blowouts start with the accidents themselves. In both cases, the pressure in the well was unusually high. The crews on the drilling platforms seem to have neglected warning signals to that effect and proceeded as usual. To save time (and money) they may even have skipped some of the safety procedures. The blowout resulted in an explosion and fire and the platform sank, damaging the stack and the well casing, causing the oil to gush into the sea from the bottom.

Subsequent attempts to stop the flow of oil were also strikingly alike, although the terminology differed. The Mexican 'sombrero' became the US 'top hat'. The steel and lead balls to be injected into the well (called "boule game") became "top kill" and "junk shot". This did not stop the oil under any name, although Pemex claimed that the measures reduced the flow. The solution in the Ixtoc case, as well as in several later marine blowouts, e.g., the Australian Montara in 2009, was the drilling of relief wells. This appears to be a likely outcome also with respect to Deepwater Horizon. It took more than 9 months for Pemex to do it three decades ago; maybe BP will manage in half that time.

The clean-up operations at sea are also quite similar in the cases. Large amounts of dispersants were used and are being used. This helps to protect birds and beaches, but increases the harm to shrimp, squid, and small fishes. Most important to the operators (and perhaps to the governments) might be that the damage becomes less visible.

Booms to contain oil and prevent it from entering sensitive coastal areas were used in Mexico and are now being used in the USA (Fig. 6). The experience then (and now) is that high waves and even moderate water flow (like in and out of estuaries) seriously reduces their usefulness. Skimmers and other devices to pick up oil from the surface were

Fig. 6 U.S. Fish and Wildlife Service officials look for oiled wildlife on various small islands near Grand Isle, Louisiana, on June 14, 2010. No oiled wildlife were found or recovered on this particular excursion. © BP p.l.c

also employed in both cases (both booming the oil off and skimming it up are actually much more difficult when dispersants have been applied). Technical improvements in this equipment over the past three decades have been marginal, thus success now is not likely to be much greater than it was then—despite a real difference between the two occasions with regard to the extent of the efforts. There are easily ten times more people, boats, and equipment engaged in the operations at Deepwater Horizon than there were at Ixtoc. When it comes to beach clean-up, the difference is even greater. Most of the Mexican beaches were just left; only close to population centers or hotels was the oil removed or, mostly, covered with sand. In the US, some 25 000 people are reportedly engaged in removing every single tar ball.

There are, of course, also a number of other differences between the two cases. One is water depth; Ixtoc was at 50 m, Deepwater Horizon is at 1500 m. Another is the coastline; the part of the coast that was hit in Mexico was mostly sandy beaches, which constituted protective barriers for the lagoons behind. In Louisiana there are sensitive wetlands. These and other differences may be important with regard to the ecological effects of the two spills.

In the Ixtoc case, crabs on beaches were severely hit. So were 2-year classes of shrimps, squid in some areas, and local populations of some smaller fish species. Extensive phytoplankton blooms in the wake of the spill also indicated that grazing zooplankton were heavily reduced in numbers.

Birds were seen as having escaped the worst in the Ixtoc case with "only" some 3000 reported casualties. Compared to many large and countless small tanker spills, the losses were seen as light. By the end of June 2010, less than 1200 dead or contaminated birds have been registered in the Deepwater Horizon case.

Turtles became a major concern as the main spawning beach of an endangered species, the Kemp Ridley Turtle, *L. kempii* was hit by oil. In an extensive rescue operation, some 10 000 newly hatched baby turtles were moved to the open oil-free sea and another couple of thousand eggs were moved to safer beach havens in the USA and on Cuba. A few dead adult turtles were collected, but the cause of death was unclear.

Five years after the Ixtoc incident, oil residues could be found on the Mexican beaches and in shallow waters. This oil was well weathered and mostly covered by sand. Where it was exposed to the air, it had lost its stickiness and crabs crawled over it and mussels and oysters had settled on it. In stretches, it had the appearance of a cracked asphalt road. Ecologically, one had to look close to see any remaining damage, and fisheries were, if anything, doing better than before the spill. The reduction of fishing pressure after the spill obviously helped the oil-affected populations to a more rapid recovery, and better equipment helped the local fishermen to catch them.

In this respect, with regard to damage to e.g., shrimp and the rapid recovery that has been seen in Mexico, there are good reasons to believe that history will repeat itself.

An obvious question after an oil spill like the ongoing one at Deepwater Horizon is what should be done to prevent it from happening again. Obviously, stricter regulations for deep-sea drilling, and at least as important, stricter supervision and control are required. From the technical point of view, development of blowout-prevention strategies should be mandated to follow the development of deep-sea drilling techniques. In the ongoing debate, it has also been suggested that R&D money should go into the development of less toxic and more effective dispersants as well as better booms and skimmers.

Personally, I have less faith in such a strategy. I believe blowouts first and foremost should be prevented, and if that fails, the capping of these blowouts should be carried out quickly and easily. To that end, as so far only relief wells seem to be reliable, oil companies should be required to drill at least two parallel holes at the beginning of operations. Thus, if needed, one of the holes could then be used as a relief well and be in operation within days, instead of months. Naturally, that will cost more, but it is a cost that oil companies can afford, and we as customers must demand and accept the oil price implications of it if we are to avoid other catastrophic long-lasting blowouts in the Mexican Gulf or elsewhere.

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