Marine Pollution Bulletin 129 (2018) 623–632

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

The potential for dispersant use as a maritime oil spill response measure in German waters[☆]

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A R T I C L E I N F O

Keywords:
Oil spill response
Dispersants
Sensitivity mapping
Environmental impact
Net Environmental Benefit Analysis (NEBA)

A B S T R A C T

In case of an oil spill, dispersant application represents a response option, which enhances the natural dispersion of oil and thus reduces coating of seabirds and coastal areas. However, as oil is transferred to the water phase, a trade-off of potential harmful effects shifted to other compartments must be performed. This paper summarizes the results of a workshop on the current knowledge on risks and benefits of the use of dispersants with respect to specific conditions encountered at the German sea areas. The German North Sea coast is a sensitive ecosystem characterised by tidal flats, barrier islands and salt marshes. Many prerequisites for a potential integration of dispersants as spill response option are available in Germany, including sensitivity maps and tools for drift modelling of dispersed and undispersed oil. However, open scientific questions remain concerning the persistence of dispersed oil trapped in the sediments and potential health effects.

1. Introduction

Oil spills can seriously affect the marine environment both as a result of physical smothering and toxic effects. The severity of an impact typically depends on the quantity and type of oil spilled, the ambient conditions and the sensitivity of the affected organisms and their habitats to the oil (Boyd et al., 2001). In case of an oil spill at sea, spill managers have to decide on the most effective spill response to minimize damage. In addition to mechanical containment and recovery using booms and skimmers, application of dispersants on the oil slick is another response option, which enhances the natural break-up of floating oil into small droplets in the water column. In this way, coating

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http://dx.doi.org/10.1016/j.marpolbul.2017.10.050
Received 6 April 2017; Received in revised form 20 October 2017; Accepted 20 October 2017
Available online 06 November 2017

of coastal areas and oiling of sea birds and mammals can be reduced (IPIECA-OGP, 2015a). Furthermore, by enlarging the overall surface of the oil, many experts provide evidence that the bio-degradation of oil by naturally-occurring marine microorganisms is enhanced (Prince et al., 2013) although these findings have been challenged (Kleindienst et al., 2015). Anyway, due to the increased concentration of oil components within the water column resulting from the oil dispersion, toxic effects on pelagic, demersal and benthic living organisms can potentially be increased (Claireaux et al., 2013).

There are conflicting views concerning the potential risks and benefits for human health and the environment generated by the use of dispersants during oil spills (Bostrom et al., 2015; Prince, 2015). Up to now, no comprehensive assessment of risk associated with the use of chemical dispersants has been developed for German marine waters, which could provide guidance for the national response organisation. Therefore, a workshop was held in November 2015 to bring together experts from authorities, research institutions and international organisations to summarize and discuss the current scientific knowledge on risks and benefits of this response strategy.

The objectives of the workshop were:

- to identify pros and cons for use of dispersants as an option for oil spill response in Germany,
- to identify options to balance risks and benefits of different treatment options, and
- to identify open scientific questions concerning the risks of dispersant application in Germany.

Summaries of the individual presentations excluding discussions held at the two day event are provided in the workshop proceedings (Grote et al., 2016). The aim of the present paper is to summarize the main results of the workshop and to lay down a common understanding and interpretation of the situation and the scientific challenges of a conceptual framework for applying dispersants in a large scale after oil spills under German responsibility. This includes

- to give an overview on current practice, guidance on and operational experience concerning dispersant use,
- to present the relevant information concerning specificities of German marine waters (geography, ecosystems, meteorology, hydrodynamics etc.), and
- to discuss specific risks and benefits of a potential dispersant application in German waters and to identify open scientific questions.

2. Current practice, guidance, effects of dispersants and operational experience

2.1. What are dispersants and how do they work?

Dispersion of oil, i.e. the break-up of larger oil volumes into little droplets, is a naturally occurring process, which depends on the oil characteristics, its weathering stage and environmental parameters such as wave energy, salinity, temperature etc. (Zeinstra-Helfrich et al., 2015). This process can be enhanced by application of specific chemical formulations, so called dispersants. Dispersants are mixtures of surfactants in one or more solvents, designed for application onto oil slicks aiming to reduce the interfacial tension between the oil and the water phase and thus increase the natural dispersion of the oil. In order to promote dispersion and work as a successful spill response measure, the dispersant must get into the oil layer, i.e. the surfactant must be able to physically mix with the polluting oil (IPIECA-OGP, 2015b). Therefore, the efficacy of a dispersant formulation will not only depend on its chemical composition but also on the chemical characteristic of the oil, environmental parameters, the application technique and the quantity of the dispersant spread onto the slick (Dispersant – Oil Ratio, DOR). If the oil is overly viscous and therefore no physical mixing is possible, chemical dispersion will not be possible in most circumstances. Dispersion is most efficient on light oil which has a low viscosity. As a general rule, the higher the oil viscosity, which is typically increased by weathering processes and by low ambient temperatures, the less efficient is the dispersion. Weathering processes encompass all chemical (dissolution, evaporation, photo oxidation) and physical (natural dispersion, emulsification) processes which will occur immediately after the release of the oil at sea and which will induce chemical and physical modification of this oil, e.g. the increase of its viscosity. Furthermore, as dispersant formulations are typically optimised for use in marine waters and in temperate climate, they prove to be less efficient in brackish or fresh water and at low temperature. However, recent work to Arctic spill response indicated that even at low temperatures dispersants can still effectively applied. Viscosity might increase, but as weathering slows down, the window of opportunity might be larger at low temperatures (Lewis and Daling, 2007).

2.2. Important guidelines concerning dispersant use (e.g. IMO, EMSA)

One major objective of dispersant use is the transfer of oil from the water surface into the water column. As a result, exposure for surface dwelling and intertidal species and contamination of coastal habitats is potentially decreased, while it is increased for pelagic and benthic organisms. Thus, inherent to the decision whether or not to use dispersants is the implicit trade-off among different habitats and species with different ecological, social, and economic values. The methodology for a predictive comparison of estimated beneficial and harmful effects of different response options is typically referred to as Net Environmental Benefit Analysis (NEBA) (IPIECA-OGP, 2015a). A NEBA is always based on the comparison of different oil spill response options which will result in specific scenarios of environmental damage to biology and ecosystem services but also includes the potential for recovery. It mainly focusses on the environment. However, as typically other aspects such as economic, cultural and human health impacts have to be considered when taking a decision on spill response measures, the term Spill Impact Mitigation Assessment (SIMA) has recently been introduced (IPIECA-OGP, 2017). These terms are not always used in a consistent way. Here we use NEBA for assessment of environmental effects and SIMA for a broader assessment incorporating other aspects.

Internationally, the use of dispersants has gained wide acceptance as one of several response options for oil spill response. The International Maritime Organisation (IMO) is currently working on revising guidelines for dispersant use providing guidance for the decision process whether or not to use dispersants in a specific case (decision tree) (IMO, 2014). Furthermore the European Maritime Safety Agency (EMSA) has published a *Manual on the Applicability of Oil Spill Dispersants* (EMSA, 2010) in European waters. Comprehensive overviews on the authorisation, preparedness and use of dispersants are provided by the *International Tanker Owners Pollution Federation* (ITOPF) and the *Global Oil and Gas Industry Association for Environmental and Social Issues* (IPIECA) (IPIECA-OGP, 2015a,b; ITOPF, 2011).

If an incident occurs, different response options are usually evaluated and may potentially be applied in parallel. The overall purpose of a practical and operational decision process is to enable relevant authorities to check swiftly whether dispersant use is an appropriate option, i.e. to verify that conditions are met to achieve satisfactory results. Considering that chemical dispersants are most efficient during the early stages/hours after the spill, it is of utmost importance that a decision is taken as quickly as possible.

It is proposed that for the decision whether to apply dispersants to a specific oil spill, the following issues should be addressed by successively answering three questions:

1. Is dispersion possible? (i.e., is the specific oil type dispersible from a physico-chemical point of view at the given environmental conditions?)

2. Is dispersion acceptable? (i.e., is the dispersion a "beneficial" trade-off from an environmental point of view?)
3. Is dispersion feasible? (i.e., is dispersion practicable from a logistical point of view?)
4. Along this process, as soon as any answer is 'no', other response options than chemical dispersion need to be applied.

The guideline for the use of dispersants for combatting oil spills at sea developed by the IMO (2014) aims to facilitate the establishment of national regulation for oil spill response organisation by outlining recommended ways to act, the requirements to be met for a sound planning and relevant criteria for decision-making at the time of the spill. The development of these guidelines in the international framework (i.e. IMO or EMSA) may help harmonizing policies at international, national and regional level.

2.3. Product approval

Dispersant product approval describes the process and criteria which a product has to fulfil for being approved for use according to national rules, and thus be in principle acceptable for use in national waters. It has to be noted that this *product approval* is distinct from a *dispersant use authorisation*, which refers to specific conditions (where, when, under what circumstances) or a specific event where an approved product is actually authorised (IPIECA-OGP, 2014). Basically, for approval, products have to be efficient (with respect to oil dispersion) and should have a low toxicity, a low bioaccumulation potential and a low persistence. However, different protocols are used to test those performance properties and to approve products in Europe (EMSA, 2016). A basic difference is that e.g., France demands toxicity information on the dispersant alone whereas the UK demands information on the toxicity of the dispersant mixed with a reference oil type. For the UK approval it is required that the oil-dispersant mixture must not be more toxic than the oil alone.

It is obvious from the long record experience from France, UK and other countries that dispersants developed during the last two decades are commonly less toxic than dispersed oil. It is generally accepted that with the modern dispersants it is the toxicity of the oil that drives the toxicological effects, not the toxicity of the dispersant (National Research Council, 2005). Due to the higher concentrations of oil components in the water phase, typically more pronounced toxic effects are observed after effective dispersion. Therefore, it appears reasonable to not apply a strict cut-off value for toxicity as this would discriminate against highly effective dispersants.

Germany has not established any approval process. However, discussions are ongoing whether this is legally or scientifically needed or whether dispersants authorised in other countries could be used on a by-case decision. Otherwise a screening and prioritisation of available products could be performed. Undoubtedly, validated efficacy and toxicity data for the dispersants are strongly needed which should allow a toxicity assessment of the dispersant-oil mixture.

2.4. Operational experience

Although dispersants are an often discussed oil spill response option, there are only a few examples of major ship-sourced oil spills for which a successful use of dispersants has clearly been demonstrated (Chapman et al., 2007). The *Sea Empress* spill (1996) in the UK where dispersants are estimated to have prevented 57,000 to 110,000 t of oil emulsions from impacting the shoreline (Law and Kelly, 2004; Lunel et al., 1997) and the *Tasman Spirit* spill (2003) in Pakistan (http://wwz.cedre.fr/en/Our-resources/Spills/Spills/Tasman-Spirit) are good examples of incidents where the net environmental impacts were considered to have been significantly reduced by dispersant application. However, in other cases, dispersants were used but were considered to have been ineffective as for example during the *Natuna Sea* spill in Indonesia in 2000. Due to the high pour point (high wax content of the oil and evaporation of volatile compounds) and sea state (low wave energy during the spill) oil solidified during the first day (Chapman et al., 2007). In other cases the use of dispersants had been considered but due to the very high viscosity of the oil, dispersant were judged to be ineffective (*Erika* spill in France 1999, *Prestige* spill in Spain 2002). Overall, thus far dispersants were rarely used in responding to incidents in European waters, which was not only related to their technical limitations but also to legislation (Chapman et al., 2007). In many cases available information is not sufficient to evaluate a posteriori whether dispersants were used in a meaningful way and whether this application was successful. However, examples cited above show that it is important to carefully consider, if the use of dispersants is a promising option for the reduction of the overall adverse effects. This identifies the need of a proper dispersants effectiveness testing and monitoring plan.

The term "successful application" in the above mentioned cases refers mainly to the observation that the dispersion of the oil was effective and that effects on the marine environment were reduced; e.g. for the Sea Empress spill, although immediate impacts to invertebrates on rocky shore and seabed were observed and thousands of seabirds were killed, most effects were temporary and pre-spill population densities were reached within 1 or 2 years (Law and Kelly, 2004). However, it is difficult to assess what would have happened if no dispersants had been used, as unlike in a lab experiment, no control situation is available to which the outcome could be compared.

2.5. Human exposure and health effects

Commonly, the assessment and concerns of adverse effects of oil spills focus on the organisms living in the aquatic environment and on the shoreline (i.e. the birds, fish, sea grass etc.) and on ecosystem services. Murphy et al. (2016) identified a longstanding gap in research on effects of oil spills on human health as only 1% of all oil spill studies address this topic. Oil spill response actions and clean-up activities involve a great number of humans. Typically at-sea response is conducted by trained responders and vessel or aircraft crews, while shoreline clean-up is dealt with by government personnel, private contractors and in some cases unskilled local labour and volunteers (Major and Wang, 2012). After the *Hebei Spirit* spill in 2007 in South Korea it was estimated that a total of 563,761 people, including 103,351 nearby residents, joined the clean-up operation, which lasted several months (Na et al., 2012). Although this is an extreme non-representative case, typically thousands of people are involved in such activities (e.g., approximately 7700 registered persons in the Prestige oil spill clean-up (Suarez et al., 2005), 1500 persons involved after the Erika spill (Institut de Veille Sanitaire, 2000) and up to 170,000 people worked in some capacity to clean up the Deep Water Horizon oil spill (D'Andrea and Reddy, 2013)). Furthermore, coastal inhabitants may be exposed by other means (inhalation, contact with the oil, consumption of sea food, etc.). Therefore, it is important to assess potential effects on the exposed populations as a result of different response options.

Health effects resulting from oil spills are often subject of debate not limited to the scientific community but also in the general public, especially regarding the influence of the use of dispersants (Dailey and Starbird, 2015). Studies on health effects related to oil spills were reviewed by Aguilera et al. (2010) and Laffon et al. (2016). Reported health effects of oil spills range from subcellular genotoxic and immunotoxic effects through physical and physiological impairments to effects on mental health (Laffon et al., 2016). However, as most studies were initiated after spill response or clean-up activities, the exposure to oil of involved population is very difficult to quantify. The commonly used method of self-reporting of estimated exposure according to the distance from the spill area or the time involved in clean-up operations, is very sensitive to bias (Laffon et al., 2016). Therefore, a causal link between exposure and observed effects cannot always be established.

This statement is even more relevant when trying to assess human health effects connected to the use of oil dispersants as it is difficult to distinguish between exposure and effects of the oil alone and a presumed oil-dispersant mixtures. Anyway, typically only 2 to 5% of modern dispersants are added to the volume of the treated oil slick. Therefore, oil-dispersant mixtures are largely dominated by mineral oil components; e.g., during the *Deepwater Horizon* incident in the Gulf of Mexico approximately 7000 t of dispersants were applied to an estimated 500,000 t of crude oil spilled of which 60% were sprayed on a relatively small ocean surface area and 40% were injected subsea (Beyer et al., 2016). Furthermore, dispersants were not used in proximity to the shore. Therefore, it is not clear to what degree the exposure of coastal inhabitants and clean-up workers was altered by dispersants.

Direct exposure to dispersants is principally possible, e.g. via inhalation of aerosols resulting from spindrift during dispersant spraying. However, this most likely concerns professional responders, which are typically experienced in the use of personal protection equipment, but also less trained and less equipped responders such as fishermen. Anyway, the application of dispersants only slightly increases the overall quantities of harmful compounds in the environment. However, it modifies the distribution of oil components between the environmental compartments according to their physico-chemical properties and may therefore potentially alter exposure routes; e.g., new exposure routes such as dermal contact with dispersed oil in water may be present. On the other hand when oil is effectively dispersed prior to reaching the shore, exposure via direct contact to oiled surfaces and inhalation of volatile oil components by clean-up workers and coastal inhabitants will be reduced. Furthermore, in this case dispersion may also reduce the overall likelihood of exposure to oil components. Health effects are often observed in the groups of people involved in clean-up activities such as beach or wildlife cleaning. By reducing the need for this kind of work, less people may be needed and thus the overall health effects may be reduced. For a comprehensive comparative risk assessment, which is the core of the SIMA process, potential additional effects resulting from exposure to oil-dispersant mixtures have to be weighed with the potential reduction of the total number of people involved in clean-up activities.

2.6. Spill response planning in UK and France

In the United Kingdom, the Maritime and Coastguard Agency (MCA) takes the lead in all significant marine incidents (Colcomb, 2016). The use of dispersants represents a primary response option to oil spilled in the marine environment. However, any use of oil spill treatment products in UK waters needs to be approved by the Marine Management Organisation (MMO) in England and Welsh Offshore waters, Natural Resources Wales (NRW) for Welsh Inshore waters, Marine Scotland (MS) for Scotland or Northern Ireland Environment Agency (NIEA) for Northern Ireland. A large amount of research has been carried out in the UK in order to underpin the approval process (e.g., Lewis, 2004; Smith et al., 2005). The MMO has the responsibility for the approval of oil spill treatment products, which have to fulfil certain efficacy and toxicity criteria (Christie, 2016). Furthermore, the MMO is also responsible for decision making on whether or not dispersant use can be allowed at the given location of a spillage in all English and also Welsh Offshore waters (Marine Management Organisation, 2016). This decision is given within 1 h of the notification of the incident (or of such a request being received). This first hour of any incident notification can be extremely demanding and involves MMO and nationally agreed expert organisations (Cefas, Natural England, Joint Nature Conservation Committee and Environment Agency) and furthermore regionally organised so called environment groups, which feed local relevant environmental information into the decision making process. The use of dispersant is not an automatic first choice. MMO will always consider whether from an environmental viewpoint it would be better to let any spillage disperse naturally. The use of dispersants will only be authorised if it was believed that this was likely to be more advantageous to the situation. No zones are identified where dispersant use is prohibited.

In France, spill response operations are under the responsibility of and are conducted by the French Navy. Scientific advice and expertise to the authorities is provided by the Centre of Documentation, Research and Experimentation on Accidental Water Pollution (Cedre) (Le Lann, 2016). Cedre is also responsible for the product approval for dispersants. It provides lab capacities for efficiency, biodegradability and toxicity testing. Although containment and recovery of spilled oil is preferred, the use of dispersant is considered a valuable response option. The decision process implemented in France is based on three accident scenarios: Dispersant use for oil spills of 10, 100 and 1000 t is possible in water depths > 5, 10 and 15 m and at a minimal distance from the coast > 0.5, 1 and 2.5 nautical miles, respectively. Protected areas are considered as “virtual islands” in the above described process whose contours are taken as equivalent to a coastline. Estuaries are also treated in a particular way. An area is calculated at the mouth of the river where chemical dispersion is prohibited in order to be sure that under no circumstances dispersed oil may enter the estuary under the effect of tidal currents. These limitations of use in specific areas are related to the dilution rate of dispersed oil required for avoidance of toxicity to pelagic and benthic organisms.

2.7. Current spill response strategy in Germany

In cases of severe oil spills, the Central Command for Maritime Emergencies (CCME) in Germany named Havariekommando (HK), a joint institution of the German Federal Government and the Federal Coastal States, takes over the command for all spill response operations at sea and on the shoreline. In such cases, the CCME would have to take the decision to use or not use dispersants, but detailed procedures for making that decision are not yet defined.

Mechanical recovery of oil is the primary response strategy in Germany and the CCME is able to activate sophisticated technology. The use of dispersants is currently not envisaged as spill response option in the German Baltic Sea area. However, since 2007, the use of dispersants is in principle possible as a secondary response option in the North Sea in cases when mechanical methods cannot be applied successfully (e.g. due to weather conditions or capacity limitations). To guide spill responders, North Sea coastal waters have been divided in 3 zones. In the open sea zone (water depth > 20 m), dispersant use is generally possible without a detailed predictive evaluation of potential effects. The water body in this area is considered to be large enough to enable a sufficient dilution of the oil-dispersant mixture and to minimize harmful effects to the marine environment. In the zone close to the shore (water depth < 10 m), the use of dispersants is not recommended with exception of locally limited use in the estuaries of the large German rivers Elbe and Weser during outgoing tide. In the intermediate zone (water depth > 10 m and < 20 m), the use of dispersants is considered as an option on the basis of a single case decision.

Responsible national authorities have not pre-approved any dispersant application and clear criteria how to decide for or against the use of dispersants are still not implemented. In 2016, in the aftermath of the workshop, a Net Environmental Benefit Analysis (NEBA) concept has been elaborated for the coastal North Sea waters of Germany as support for the decision making but it has not yet been implemented. The dominant strategy in German response planning today remains the removal and containment of spilled oil by mechanical technology. Equipment acquisition and training has mainly been focussed on this mechanical recovery. Currently no dispersants are stockpiled and no dispersant-specific equipment is acquired.

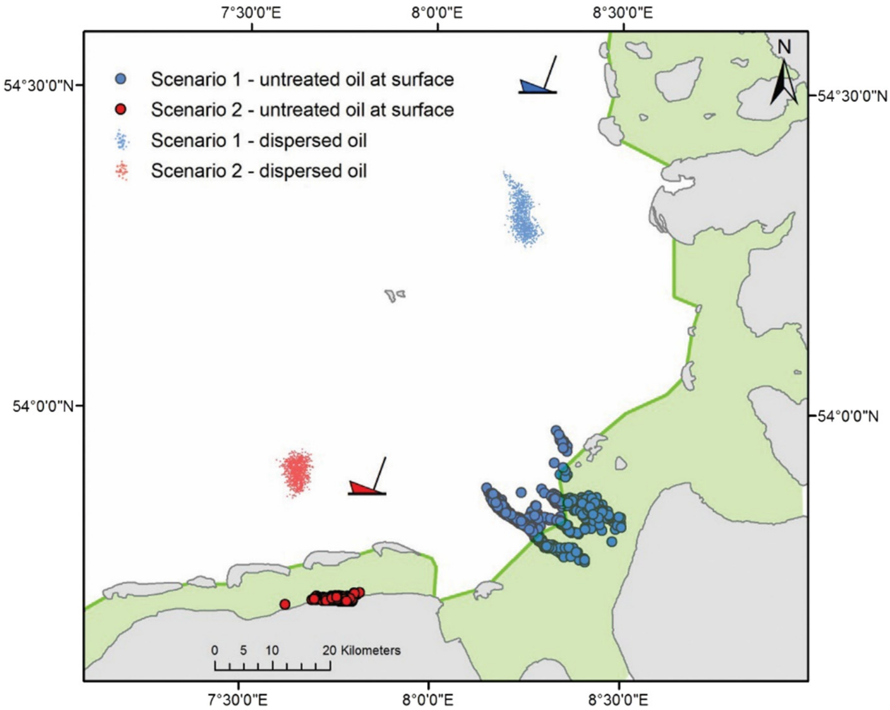

Fig. 1. Ship symbols (red and blue, respectively) indicate two locations of hypothetical oil releases. Dots represent simulated locations of the pollutant five days after the assumed time of an accident (here: 15th of March 2008 at 04:00 UTC). Large dots represent oil at the surface, small dots oil droplets in the water column. Green areas indicate tidal basins (Wadden Sea) that are considered particularly sensitive. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Specificities for dispersant use in German coastal areas

3.1. Coastal and marine ecosystems

Germany has two different sea areas: the North Sea (German Bight) and the Baltic Sea, which are both characterised by very specific ecosystems.

The German North Sea coast is characterised by a contiguous region of tidal flats, barrier islands, alluvial terrestrial zones and salt marshes, and an up to 25 km wide intertidal zone called "Wadden Sea" (Reise et al., 2010). It is rich in biological diversity and is of enormous value as a cleansing site for the coastal water, as a nursery for young fish, and as a feeding and nesting ground for nearly all palaearctic species of wading birds and waterfowl. The Wadden Sea is one of the most important areas for migratory birds in the world. It is part of a network of sites along the east Atlantic flyway that is used each year by 10–12 million birds migrating between their breeding grounds in the Arctic and their wintering sites in Western Europe and along the western seaboard of Africa. Together with similar areas in neighbouring Netherlands and Denmark, the Wadden Sea has been inscribed on UNESCO's World Heritage List (http://whc.unesco.org/en/list/1314). The German Wadden Sea National Parks represent a total area of 8000 km^2, of which approximately 30% are intertidal areas. Other unique biodiversity hotspots are the rocky shores and bird rocks of Helgoland, an island in the centre of the inner German Bight, which is very sensitive to oil pollution as it accommodates the entire nesting population of certain bird species (e.g. northern gannet and common murre) and serves as resting place for migrating birds. Important shipping routes into the major ports of Hamburg, Bremen/Bremerhaven, Wilhelmshaven and Emden run close to or cross these ecosystems. Furthermore, the entrance to the Kiel Canal connecting the North to the Baltic Sea is accessible through this area. Therefore, ship casualties in this ecologically sensitive zone cannot be excluded.

The Baltic Sea is a semi-enclosed brackish sea area, which has limited exchange of water with the outer North Sea. The German stretch of the Baltic Sea is characterised by salinities of around 17 psu in the western part and 8 psu in the eastern part and an average water depth of 18 m. It has a unique morphology characterised by fjords, lagoons and backwaters providing habitats for an abundant fauna and flora. The Baltic Sea is an area of dense shipping traffic, including international ferry connections and oil tankers delivering Russian oil to refineries worldwide.

3.2. Efficiency of dispersants in German waters

The efficiency of a dispersant depends on different factors: oil type, weathering stage, temperature, sea state and salinity (Zeinstra-Helfrich et al., 2015). In the North Sea, water temperatures typically vary between 2 °C in winter and 20 °C in summer with an annual mean of 10 °C. The salinity is at 35 psu but considerably lower in the brackish estuary zones. Depending on a location's distance to the coast, the average significant wave height assumes values between 1 m and 1.5 m (Staneva et al., 2014). A minimum wave height and resulting turbulence are required for effective dispersion. On the other hand, too high waves make dispersant application infeasible and also less necessary in the presence of effective natural dispersion. Based on retrospective model simulations, Schwichtenberg et al. (2017) estimated that, depending on the specific location, conditions unfavourable for dispersant application (wave heights outside the range of 0.5 to 3 m) are present during 20–30% of the time. However, this rough estimate does not yet consider the specificities of the oil type and its weathering state.

In the Baltic Sea, temperatures are more variable and salinity is significantly lower compared to the North Sea. Furthermore, the sea is commonly less rough, thus providing less mechanical energy for dispersion. In contrast, lower wave height enables mechanical recovery of the oil. Due to the limited water exchange and the low water depths, dilution of dispersed oil is likely to be limited and slow. Therefore, on average the conditions in the Baltic Sea are less favourable for dispersant use.

3.3. Dispersion influences oil drift

The decision to use dispersants or not will depend on the physicochemical conditions at the spillage site. When dispersion of an oil slick is possible, spreading of the dispersed oil must be estimated in order to assess potential toxic effects of the oil-dispersant mixture. Local tidal conditions, winds, currents, waves and similar factors will all influence oil behaviour. For identifying the least harmful management option, a comparison between the expected movements of untreated oil and an oil-dispersant mixture is essential. In this respect, hydrodynamic modelling provides valuable information. As an example, (Schwichtenberg et al., 2017) performed simulations for hypothetical oil releases at two different locations within the inner German Bight, assuming oil being present either as untreated surface slick or completely dispersed. Fig. 1 shows the model outcome based on winds and currents during 15 to 20 March 2008.

In order to examine the variability of potential scenarios under realistic conditions, Schwichtenberg et al. (2017) studied a large number of hypothetical events, assumed to have occurred at 636 different locations every 28 h in the years 2008–2014. For each of these 2190 simulations per location, the percentage of released oil entering the Wadden Sea (green zone in Fig. 1) within a week's time was quantified both with and without application of a chemical dispersant. While untreated oil was assumed to drift as a surface slick (not taking into account oil weathering processes), dispersed oil was assumed to be fully mixed into the water column. The two idealized extremes were meant to enclose the range of possible developments that may occur in reality but are difficult to predict in full detail. Fig. 1 displays just two example events from the large ensemble of 636 × 2190 events studied. At the specific time (15 March 2008, 04:00 UTC), without dispersion much or even all of the oil hypothetically released at one of the two locations (red or blue) would have entered the Wadden Sea. By contrast, after its assumed complete dispersion the pollutant stays in the open sea. Evaluation of all simulated releases confirms that in most cases dispersed oil would have affected the Wadden Sea to a much lesser extent than untreated oil. These results reflect the predominance of onshore winds that impact oil slick movements at the water surface. After dispersion, this direct wind drag disappears and pollution transport depends exclusively on marine currents.

Schwichtenberg et al. (2017) summarized their results in terms of rough estimates of the probabilities that chemical dispersion would be beneficial at different locations within the inner German Bight. They concluded that for many regions in the inner German Bight, an application of chemical dispersants can be expected to substantially reduce pollution of tidal flats. Note that in case of a real spill case specific model results would be available, predicting the drift paths under these specific conditions, both with and without dispersion (Broström et al., 2011).

3.4. Effects on tidal flats

A large proportion of the North Sea coast is composed of tidal flats. When submerged, typically low water depths prohibit oil spill response vessels to enter and efficiently operate for mechanical clean-up. However, when emerged, this area is hardly accessible from land by machinery due to the muddy substrate. Also from a risk perspective it is not wise to use machinery as it might push down the oil into the sediments. Besides the high ecological sensitivity to oil pollution, this is why high priority has to be given to avoid oil entering this zone.

Depending on their lipophilic nature, oil components tend to bind to organic matter in the sediment (Gong et al., 2014). It is however unclear whether dispersed oil enters into deeper sediment layers more than undispersed oil. It is therefore essential to understand the processes leading to the accumulation of oil components in sediments. How and to what extent will this phenomenon be influenced by the use of dispersants and would this process be reversible? It has to be assessed whether dispersed oil in the interstitial water of the upper sediment layers is less or more harmful to benthic organisms than an oil slick coating.

Effects of chemically dispersed oil on benthic communities in German North Sea tidal mud flats were first studied in the 1980s (Farke et al., 1984, 1985a,b, 1992) using in situ “caissons” allowing a localised and well controlled exposure situation. In all experiments, the dispersed oil accumulated only at the surface of the sediment, with little penetration into deeper layers (Farke et al., 1985b). The authors concluded that, as no deep sediment layers were seriously contaminated, a state of chronic pollution may be avoided by dispersing the oil (Farke et al., 1985b). However, only low concentrations of dispersed oil have been used. Therefore, it is not clear whether high concentrations that could be present during an oil spill would behave in a similar way. At that time, modern dispersants with low toxicity were not yet developed and sensitive chemical analytical techniques were not available as today. It is concluded that studies based on up-to-date scientific and technical standards using dispersants of today are urgently needed to permit a reliable scientific assessment of relevant exposure scenarios for the Wadden Sea.

3.5. Recovery potential

After the reduction of the number of individuals in local populations or communities as a result of acute toxic or physical effects, a re-establishment of organisms at the site is often observed after the concentration of the toxic compounds has decreased (Liess and von der Ohe, 2005). Concentration changes of the toxic compounds depend on the compound specific persistence in water and sediments and on potential dilution effects. However, the potential for recolonization depends on numerous species specific factors: (i) sensitivity/tolerance to chemicals, (ii) potential for (im)migration from non-impacted areas and (iii) the reproduction dynamics (generation time, number of offspring) (Van Colen et al., 2008). In general, ubiquitous species with high reproduction rates and short generation times (r-strategist) have a significantly higher potential for recolonization than isolated species with a slow reproduction (k-strategist). Therefore, populations of sea birds and sea mammals are typically characterised by much lower recovery potentials than benthic or pelagic invertebrate species.

The caisson experiments from the 1980s showed that there was a rapid recovery of the benthic community after the exposure to oil and oil-dispersant mixtures. Furthermore, the concentrations of oil components decreased rapidly after the caissons had been removed (Farke et al., 1985a,b, 1992). It is however not evident, whether this decrease was related to biodegradation or whether simply concentration in local sediments were diluted by tidal water particle movements. Deis et al. (2017) demonstrated that full recovery of heavily oiled salt marshes will take longer than 5 years. Other studies show that acute effects of spilled diesel oil on benthic communities in tidal flats can rapidly be recovered (Egres et al., 2012). Further research is necessary.

As described above, the Wadden Sea is a unique ecosystem with much specialised fauna. Due to its extension (8000 km^2 for the German part) with specific recurring similar habitat types there is a large potential for recolonization. The potential for recovery has been demonstrated in long-term studies on artificially defaunated plots in the Wadden Sea (Beukema et al., 1999). Furthermore, in early spring 1996 a huge algal bloom caused extensive oxygen depletion and a subsequent toxic hydrogen sulfide production leading to the death of large parts of the zoobenthos in 7.9% of all mud surfaces of the East Frisian Wadden Sea (“black spot” phenomenon) (Behrends et al., 2004). Against expectations, complete recolonization took place within a few months during the windy summer. These cases show that populations of organisms living in the sediment can recover from acute toxicity rather quickly in such ecosystem. Therefore, recolonization in this compartment is likely as soon as concentration of toxic oil components drop below critical values.

3.6. Sensitivity mapping

Sheltered tidal flats, salt marshes and adjacent estuaries belong to the types of coast which are most sensitive to oil pollution. Since it is not possible to protect the entire German North Sea coast equally at all levels, oil spill contingency planning requires a more detailed classification. For this reason, individual soft bottom habitats, communities and stocks of salt marshes, macrofauna, waterfowl and estuarine biotope types were evaluated and classified according to their vulnerability to oil pollution. The sensitivity of a particular area to oil contamination depends largely upon the physical characteristics of the habitat, the susceptibilities of individual species and their ecological properties within the communities (van Bernem et al., 2000).

Thus, essential background knowledge for oil spill response planning is information on the environmental sensitivity of the entire area. A detailed sensitivity map of the German North Sea Coast has been elaborated based on comprehensive field surveys, which were initiated during 1978–1986 (Dörjes, 1984; van Bernem, 1982, 1984). The results of these field surveys, complemented by those of the international literature and case histories, allowed a classification of species assemblages, sediments and habitat-types according to their sensitivity to oil pollution. Consequently a field-mapping was required to determine the distribution of these entities in the "Wadden Sea".

After a feasibility-study (1987–1989), the mapping of the entire intertidal areas of the German North Sea coast could be completed in 1992 and revisited during 2002–2006 (van Bernem et al., 1989, 2007; van Bernem, 1991). This "Thematic Mapping and Sensitivity Study of Intertidal Flats" is a combination of estimated and measured values, collected along a grid net of locations with 1 km interval. In total, throughout the years about 5000 locations were characterised using about 70 parameters for each site. The characterisation of areas was achieved by extrapolating these values onto the circumjacent habitat-type.

The values encompassed, for example, information on the presence of micro- and macroalgae, macrofauna species, surface structure (i.e. ripple, colour) and sediment characteristics (grain size, shear strength, water content). The basis of all evaluations is species diversity and abundance as well as qualitative parameters of the sensitivity of individual species. In the case of benthos, aspects of their importance within the systems are included by weighted values referring to the following categories: "physiological sensitivity to oil", "ecological sensitivity to oil" (i.e., ecological traits that influence exposure, e.g. endobenthic organisms are less exposed to a short term oil contamination than epibenthic species, filtering species typically show a higher ecological sensitivity than predators), "importance as a source of food", "importance for metabolisation of organic matter", "ability to spread" (migrate), "isolation", "duration of reproductive stages".

All above aspects are integrated into one characteristic benthos index, the calculation of which is based on an automated expert system employing neural network techniques and advanced classification methods (Schiller et al., 2005). A further temporal aspect of sensitivity is based on the presence of breeding and migratory birds, monitored by National Park authorities. Combining this information with the benthos index provides for each of four seasons an index that discriminates between four classes of overall oil sensitivity, ranging from low (green areas in Fig. 2) to very high (magenta). Generally, only the highest sensitivity value is assigned to saltmarshes, sea grass, mussel beds and bird stocks. The resulting digital map was implemented into a geographic information system (GIS) Tool (VPS.sensi, see Fig. 2). Main user of this tool is the Central Command for Maritime Emergencies (van Bernem et al., 2007; Baschek et al., 2016).

4. Risks and benefits of dispersant use in German ecosystems/status of discussion

In order to assess risks and benefits of different spill response options, their potential adverse effects and the potential for recovery must be compared. In the event of a mineral oil spill, the simulated drift of the surface oil slick can be contrasted with a corresponding simulation of a dispersed oil plume. Combining this information with the sensitivity map, potentially exposed habitats can be identified and potential effects be estimated. In this way, a basis for an informed decision on the optimum spill response measure can be obtained.

One central question in each NEBA process is how to trade off different potential effects, e.g. acute toxic effects in aquatic (benthic) organisms that would not be affected otherwise with regard to potential avoidance of oiling of birds and coastal areas. For the conception of a meaningful NEBA, protection goals and protection priorities have to be clearly identified. Science can contribute to this prioritisation, but to a certain degree this will be a societal and political decision. As a lot of uncertainties are involved, it is difficult to anticipate the net benefit of a specific action. However, one goal of the NEBA preparation should be to identify cases for which one response option is more beneficial than the other.

For a prioritisation of protection goals, higher priority should be given to endangered or rare species or habitats especially when having low recovery potential. This would particularly apply to nesting and resting sites of sea birds and sea mammals. Lethal effects on biota can be acceptable as a part of the NEBA trade off, if populations can quickly recover as a result of high reproductive capacity combined with short generation cycles and/or possibilities for immigration from adjacent non-impacted similar habitats.

Detailed sensitivity maps of the German North Sea coast habitats have been elaborated, which allow in principle a season-specific ranking of different zones with regard to their sensitivities towards oil pollution. Furthermore with drift models based on real-time weather and hydrological current data (Broström et al., 2011), a working tool is available that enables prediction of the drift paths of both surface oil slicks and fully dispersed oil plume. Such two predictions combined could provide an excellent basis of an informed decision on the most beneficial management option. However, this approach is not fully established as long as clear criteria for a prioritisation of management options are lacking. Thus far, in Germany only general sensitivities to oil contamination were mapped (varying with seasons) not distinguishing between sensitivities towards oil slicks and dispersed oil respectively. In 2016, a NEBA approach was developed for the German North Sea coast but it is not yet publically available and it has not yet been implemented.

In addition to environmental effects, a SIMA has to take into account ecosystem services such as economic, cultural and human health aspects. Oiling of beaches and sea birds typically leads also to human exposure. Especially, cleaning of oiled seabirds can lead to high incidents of health impairments (Baars, 2002; Suarez et al., 2005). Furthermore, as many parts of the North Sea coast are tourist areas, human exposure is likely when oil slicks reach the shore especially if "disaster tourism" is considered. Therefore, a comprehensive SIMA will have to integrate on environmental, human health and cultural/social hazards.

5. Discussion and non-answered questions

5.1. Zoning

One central element in response planning is the definition of circumstances under which the use of dispersant would be allowed or pre-approved. This can be established by the definition of zones where an application is either admissible or prohibited. It is important to take seasonality into account for zoning as sensitivities of areas may shift due to the presence or absence of species or sensitive life stages. This zoning has important advantages as it facilitates rapid decision making in case of a spill incident. In most zoning approaches, the use of dispersants in coastal zones is not allowed, e.g. France uses cut-off values for water depth (> 5 m, > 10 m, > 15 m) to define different geographical limits for dispersant application in relation to the amounts of spilled oil. The scientific argument for this zoning is that concentrations in the water phase above the sediment surface should not reach toxic levels. However, this approach anticipates one central element of the NEBA process, i.e. the trade-off between different harmful effects. By

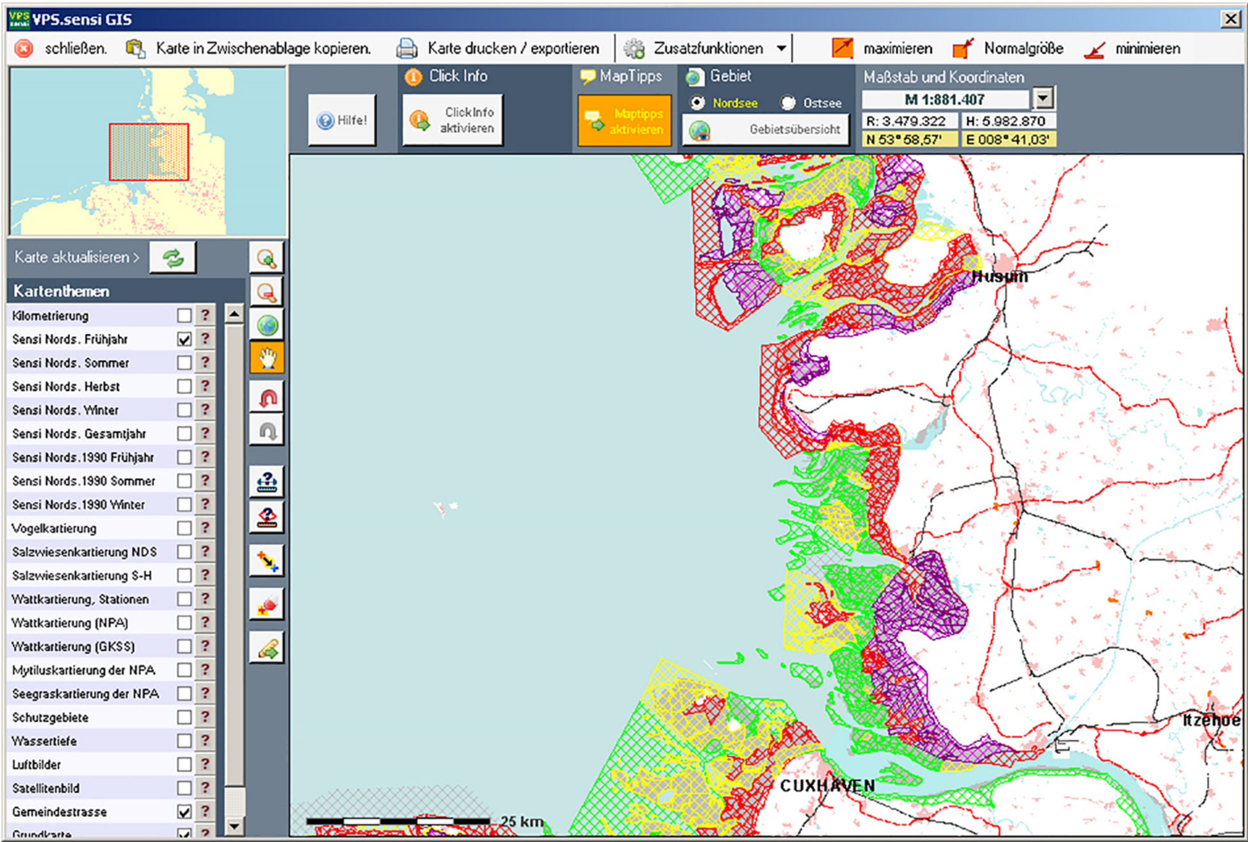

Fig. 2. Example of the sensitivity model used by the Central Command for Maritime Emergencies. Increasing sensitivity is marked by the colours from "green" over yellow, light red to dark red. The scale on the left allows selecting different topics of the underlying data base (for example: different seasons, saltmarshes, seagrass, and aerial images). (For further information see: https://www.vpsserver2.de/vpsweb/vps_info/vps_info_en/vps_sensi/nordsee_ziele_en.aspx). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

using a strict zoning approach, one protection goal may implicitly be given higher priority. For German coastal waters, a definition of zones depending on the water depth would have a large influence on the possible application areas as waters in the German Bight are shallow and subsequently zones would be very wide. Anyway, as described above, the central question for the dispersant application is not where the spill occurred or where the dispersants are used, but where the oil slick or the oil dispersant plume will drift to. Furthermore, it was discussed whether limits could be linked to the water exchange rate. In this case, water exchange rates regarded as sufficient for safe dispersant use need to be defined.

5.2. Shifting of effects

One major aim of dispersant use is to transfer the oil from the water surface to the water body in order to reduce wind drift and to keep the oil out of sensitive areas (e.g. the Wadden Sea tidal flats and seabird colonies during the breeding season). However, even in situations where oil drift is not threatening sensitive habitats, oil could be removed from the surface and mixed into the water column when effects on pelagic organisms are considered acceptable and accelerated biodegradation is expected. As such the physical shift of oil from one phase to the other, implicitly involves a shift of effects from one group of organisms to others.

However, any decision in the trade-off between harmful effects can be criticised. Protection goal priorities may not be homogeneous between different stakeholders such as fishermen, tourism managers or environmentalists. It is unlikely that a specific response is considered as optimal by all parties. Also, one has to deal with criticism like claiming that visible effects are shifted to less visible effects. It appears therefore essential to be as transparent as possible in the decision making process. The discussion on protection goals has to be broadened and opened to stakeholders involved in order to assure that a certain level of agreement is reached. In this way, public acceptance of spill response measures can be increased. Decision making processes and underlying information leading to decisions taken should be accurately documented.

5.3. Health effects

With respect to health effects, the use of dispersants may shift exposure routes from e.g. direct contact to oiled surfaces and inhalation of volatile oil components towards contact with dispersed oil in water and inhalation of aerosols. On the other hand, a reduction of oiled surfaces and birds would possibly result in a lower number of people involved in clean-up, which would consequently reduce the likelihood of exposure. However, a reliable assessment of the overall impact of dispersant use on human exposure and potential health impairment is still needed.

There is a clear need for the design and preparation of epidemiological surveys for future spills as an integral part of response planning in order to being able to start studies during the initial phase of the clean-up activities including exposure measurements and options for long-term follow-ups. It appears therefore essential to prepare the exposure assessment and medical follow-up of potentially exposed populations as an integral part of monitoring plans in the spill response preparedness planning in order to "not being obliged to only pick up the remnants of scattered health data" (Reardon, 2011). In this way, a more detailed understanding of causal links between exposure to oil components and chemical dispersants and health impairment will be possible, which will allow a more information based debate.

5.4. Product approval

Different approaches for product approval in Europe were established in France, the United Kingdom, and Norway. The objectives are similar: approve efficient products with low toxicity. However, tests and approval criteria could not be harmonized in the past. Dispersants of the latest generation generally are more efficient and less toxic to aquatic organisms than the former products. With modern dispersants, the concern of toxic effects has thus shifted from the products themselves to the toxicity of the dispersed oil. Testing dispersants with all kinds of mineral oils within an approval procedure is not feasible. The UK therefore went for a standardised "typical" mineral oil type whereas in France, only toxicity of the dispersant alone is tested. French experts argue that information on toxic effects of the dispersed oil are not indispensable for approval and would be better integrated in the NEBA as they depend on the specific type of oil spilled. It was concluded that the different approval procedures in France and in the UK did not result in approvals of significantly different dispersant products. A number of products are accepted under both approaches and are thus covered by stocks offered by the EMSA for European use.

There was a common understanding between the German workshop participants that products have to be approved prior to use and that an authorisation process has to be legally established. As only very few laboratories in Europe are equipped to do the testing, a German regulation could refer to testing practice and approval criteria already established in one country of the European Union, e.g. France in order not to further diversify approval conditions.

6. Conclusion

The aim of this paper was to document the outcome of workshop discussions dealing with risks and benefits of the use of dispersants at the German sea areas. It could be shown that many prerequisites of a potential integration of dispersants as spill response option in Germany are available, including sensitivity maps and tools for drift modelling of dispersed and undispersed oil. However, open scientific questions remain concerning degradation of oil components and potential health effects. Based on available information a NEBA has been developed. The revision of the spill response planning and the scientific evaluation of different response options are still ongoing.

Acknowledgement

The workshop and the study were financed on internal funds of the Federal Institute for Risk Assessment and did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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