OIL SPILL RESPONSE PLANNING TOOLS FOR COLD AND WARM WATER ENVIRONMENTS – A COMPARATIVE REVIEW

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ABSTRACT

#688879: The priorities for oil spill response (OSR) are to protect people, prevent or mitigate environmental damages, and minimize the long-term impacts. Several analytic approaches have emerged in the field of spill impact mitigation assessment (SIMA), a science-based framework evolved from net environmental benefits analysis (NEBA), to broaden the focus from consideration of mitigation of ecological impact to also include socioeconomic and cultural impact considerations. In the northern Gulf of Mexico (GOM), a comparative risk assessment (CRA) decision-support tool was developed for identifying and comparing the ecological consequences of different oil spill response technologies in temperate/sub-tropical deep water, including the use of subsea dispersants. Another analytic assessment tool, Environment & Oil Spill Response (EOS), was developed based on offshore western Greenland and the Baltic Sea to assist in selection of oil spill response options that best mitigate the

consequences of spilled oil in polar / sub-polar aquatic ecosystems in the Nordic region. In this work, we briefly review the CRA and EOS tools and highlight the shared and unique attributes of both assessment frameworks and how ecological, environmental and oil chemistry characteristics are handled in contrasting climatic and ecosystem conditions.

INTRODUCTION

When oil is spilled into open water and coastal marine environments, the first priority for oil spill responders is the protection of the public and oil spill response personnel, followed by source control. Once those priorities have been addressed, the goals of oil spill response (OSR) shift to minimization of the overall environmental and socioeconomic impacts. There are several oil spill countermeasures in use around the world that, depending on oceanic and climatic conditions, can be deployed – such as mechanical removal, in-situ burning and the use of dispersant substances. Each countermeasure provides varying levels of effectiveness in different environments with respect to stemming the spread of a spill and potential short-term and long-term environmental impacts (Wegeberg et al. 2017).

The selection of appropriate response option(s) depends upon different types of ecological, environmental and oil fate information specific to the relevant spill location (NRC 2014). as well as understanding aquatic life at risk of potential exposure and information conveying insights on the resilience of the environment to the consequences of spilled oil and response actions (Robinson et al. 2017).

There are different types of assessment methods, ranging from complex models to relatively simple screening procedures, have evolved to assist spill emergency responders with a systematic method for incorporating complex scientific knowledge and prior relevant spill experience into OSR decision making (Wenning et al. 2018). The spill impact management assessment (SIMA) is a relatively recent refinement specific to OSR evolved from the broadly applied discipline of net environmental benefits analysis (NEBA) and similar risk assessment approaches (Taylor et al. 2018).

However, governmental authorities and industry stakeholders must be cognizant of the limitations inherent to scientific information and assessment methods when preparing to undertake an OSR assessment. Much of the available data and world's oil spill experience is relevant to temperate and sub-tropical environmental conditions, and may not be useful to environmental protection priorities or response strategies in other climatic regimes (Wenning et al. 2018; Jørgensen et al. 2019).

Nonetheless, all frameworks share a common approach for selection of spill response options, that is based on the results of risk and impact assessment (in addition to legal requirements and international conventions) and trade-offs to derive best courses of action. The trade-offs generally reflect a balance between the protection of different types of resources in different environmental compartments and their ecological and/or socioeconomic value, with human health as the over-riding first priority in any spill response action. These valued ecological and socio-economic resources are also likely to possess varying sensitivities to direct or indirect contact with spilled oil, its weathered constituents or by-products from OSR activities. The different capacities of these resources to recover after the spill event is another important factor in decision-making for deployment of OSR technologies.

This work reviews two environmental assessment tools developed to support oil spill response in connection with oil transportation and exploration activities in two different regions of the world. A comparative risk assessment (CRA) tool developed to support oil & gas exploration and development in the northern Gulf of Mexico was tailored specifically to simulate spill conditions and predict ecological consequences in a temperate / sub-tropical aquatic environment. The Environment & Oil Spill Response (EOS) tool, was developed initially to examine the consequences of spilled oil in polar / sub-polar aquatic environments. A comparison of the similarities and differences offers an opportunity to examine shared assessment attributes, as well as the key considerations that distinguish oil spill response assessment in starkly different climatic regimes. It is evident from this work that an understanding of the different information for conducting assessments for the different climatic environments (temperate/sub-tropical and arctic/sub-arctic) is needed. Hence, such comparison, also with a discussion of common areas of research and technical improvements, emphasises the need to advance our knowledge of oil spill trajectory and dispersion modelling, ecological conditions, and ecotoxicology of spilled oil.

CRA AND EOS SPILL ASSESSMENT TOOLS

Northern Gulf of Mexico CRA Tool

In the aftermath of the Deepwater Horizon oil spill in 2010, scientists and regualtory agencies pursued new research regarding the efficacy of chemical dispersants and, in particular, the use of subsea dispersant injection (SSDI) as a viable countermeasure for deepwater oil well blowouts (Beyer et al. 2016, Brandvik et al. 2017). In 2018, a series of papers were published describing a Comparative Risk Assessment (CRA) approach for evaluating the consequences of SSDI use relative to other spill response actions, including mechanical recovery, in-situ burning, and surface dispersant applications (French-McCay, et al. 2018; Bock et al. 2018; Walker et al. 2018). The CRA approach involved probabilistic modeling to evaluate the influence of variable metocean conditions (i.e., winds, currents and temperature) on oil trajectory and fate (French McCay et al. 2018), coupled with a comparative risk assessment methodology to compare the ecological consequences in different environmental compartments to various OSR actions (Bock et al. 2018). The aim of the work, sponsored by the American Petroleum Insititute, was to provide quantitative information to decision makers so they could evaluate the potential consequences and tradeoffs associated with the use of dispersants, in situ burning and mechanical removal activities.

The tool synthesizes data on environmental compartments (ECs), the Valued Ecosystem Components (VECs) inhabiting those compartments, oil spill fate and transport modeling, the efficacy of OSR options, and the exposure of VEC to spilled oil. A series of calculations are used to derive a CRA score that can be used to evaluate the hypothetical responses of different ECs and VECs to the deployment of different OSR options.

Western Greenland / Baltic Sea EOS Tool

In the northern North Atlantic Ocean, climate change is reducing oceanic and coastal ice conditions and creating new opportunities for shipping routes and oil and gas exploration and development. During the last decade the level of ship traffic, including tourism, and mineral exploration activities have been increasing in and around Greenland (Wegeberg et al. 2018). This trend is expected to continue and places the Greenland marine environment at higher risks of shipping accidents and oil spills (Christensen et al. 2017). The seas surrounding Greenland are important areas for fisheries, seabirds and marine mammals, and for these environments, and other cold subarctic and arctic seas, oil pollution may have serious ecological and socioeconomical consequences (Riget et al. 2018, Wegeberg et al. 2018). Further, given the remoteness, limited infrastructure and harsh weather conditions (storms, ice, darkness), there is an urgent need for OSR preparedness.

As part of the European Union (EU) Horizon 2020 research project GRACE (Integrated oil spill response actions and environmental effects), the EOS analytic tool was developed for cold climate and ice-infested areas of the North Atlantic and the Baltic Sea (Jørgensen et al. 2019). The aim was to develop a tool that supports decisions on oil spill response strategies based on analysis of the consequences of oil spill scenarios and oil spill response techniques, including the ecological and potential human consequences (Wegeberg et al. 2016). Because several approaches have already been proposed in the polar region, each catering to specific governmental or environmental requirements that inhibit broad application (Wenning et al. 2018), the EOS tool was developed purposely with broader applications than just to the coastal and nearshore Western Greenland and Baltic Sea.

The EOS tool is available on the Internet (https://bios.au.dk/forskningraadgivning/temasider/environment-oil-spill-response-eos/). The EOS tool involves 5 steps. The first step is compilation of basic data and information, either from site-specific studies or polar research conducted elsewhere, and includes presence of Valued Ecosystem Components (VECs) in sea surface, seawater, sea bed and shoreline spatial compartments, segregated by season. Step 2 includes assessments and calculations based on the data compiled in Step 1. Step 3 is the calculation of scores from a series water quality, oceanic and coastal environmental features, and biota and ecological consequences. Step 4 consists of decision trees for the use of oil spill response techniques and is used to evaluate if the different spill response technologies are recommendable in the assessment area or not. Lastly, Step 5 is an interpretation and decision-making step to communicate findings to stakeholders (Wegeberg et al. 2019, 2020).

SHARED ATTRIBUTES OF THE CRA AND EOS TOOLS

The common framework for OSR assessment, whether in warm or cold water environments, includes oil spill modelling simulations, which gives basic information on modelled fate of the oil type and volume in the environment (Liungman and Mattsson 2011, Arneborg et al. 2017, French-McCay et al. 2018). Both the CRA and EOS tools analyses initiate with the formulation of hypothetical oil spill scenarios to define the spatial distribution, dispersion and fate of the spilled oil likely at a particular time of year. Model outputs, including spill trajectory, concentrations of the spilled oil, naturally dispersed and evaporated oil fractions, and behaviour in different environmental compartments (e.g., sea surface, seawater, seabed, shoreline), are incorporated into both the EOS and CRA tools (French McCay et al. 2018, Wenning et al. 2018, Wegeberg et al. 2019).

In addition to modelling, the shared assessment attributes of the two analytic oil spill response tools (CRA and EOS) include the definition of environmental/spatial compartments, identification of VECs, oil exposure screening threshold values, recruitment and recovery potential for the VEC populations (Table 1). The environmental compartments, such as sea surface, upper and lower epipelagic water column depths, and sea bed are inhabited by different VECs. The VECs may be exposed to and effected by the spilled and treated oil differently, as well as population recovery and potential recruitment may depend on reproduction time and population sizes (Bock et al. 2018, Wegeberg et al. 2020, 2021).

Table 1. Shared assessment attributes of the Comparative Risk Assessment (CRA) and Environment & Oil Spill Response (EOS) assessment tools. Based on Bock et al. (2018); Wegeberg et al. (2020); and Wegeberg et al. (2021).

Assessments attributes	Analyses input
Environmental compartments	Habitats/ecosystems inhabited with different organisms, which may be impacted differently from the oil pollution according to the location of the oil spill, e.g., on the sea

	surface, dispersed oil in the seawater column or beaching oil on the shoreline.
Valued ecosystem components (VECs)	VECs are species or organism groups of concern, which may, e.g., be species that are key organisms in the ecosystem, red listed, national responsibility, commercially important, iconic or stakeholder selected.
Ecotoxicology	For calculation of the seawater volumes exceeding oil exposure screening thresholds values with respect to impact from untreated and treated oil on VECs as well as sea surface area regarding oil sheen or oil slick thickness that may harm seabird feather structure.
Recovery and recruitment	VEC resilience and potential for recovery following exposure to spilled oil and OSR activities is based on population dynamics including recruitment from outside the impacted area and reproduction time. Hence, life span, or generation time, was used as a proxy for recovery time and population density for recruitment potential.

PARAMETERS UNIQUE TO EITHER WARM OR COLD WATER ENVIRONMENTS

Region-specific ecological and environmental assessments, as well as differences in untreated and treated oils' fate and effect, necessitate different considerations and input data to the EOS analysis and CRA when evaluating oil spill conditions in cold and warm water environments. Operationally, oil spill fate and the operability of OSR methods are highly dependent on air and sea temperature with respect to behaviour of the spilled oil type. Hence, low water temperatures tend to increase oil viscosity leading to reduced removal efficiencies for some of the OSR methodologies (Lewis and Prince 2018). There are instances, however, when colder climatic conditions are advantageous to spilled oil removal because sea ice conditions can slow down the emulsification process of spilled oil and extend the window of opportunity for certain OSR technologies to be successful (Janne Fritt-Rasmussen 2017).

The CRA and EOS analyses tools both build on a common set of environmental attributes (Table 1). However, the tools were initially developed to focus on different region-specific characteristics, reflecting the large differences in the climatic and ecosystem conditions exemplified through the CRA application to spill conditions likely in the Gulf of Mexico and EOS application to spill conditions likely in the Arctic (Table 2, Table 3).

There is a marked difference, in particular, regarding strong seasonality in the northern North Atlantic Ocean relative to the Gulf of Mexico, which can bring profound periodic changes in air and water temperatures, presence / absence of ice, daylight conditions (from 24 hours of light to complete darkness), changes in VEC populations and biodiversity (Bejarano et al. 2017, Aune et al. 2018, Helle et al. 2020). For some VECs, there are adaptation to this seasonality that change their sensitivity to oil pollution; e.g., changes in the lipid content of copepods as well as some fish between summer and winter has been shown to alter susceptibility to exposure to spilled oil (Hansen et al. 2016, Agersted et al. 2018, Fahd et al. 2019).

Table 2. Specific considerations on the fate of oil spills in relation to a temperate/sub-tropic (warm) and arctic (cold) water environment based on the CRA (Wenning et al. 2018) and EOS tools input (Wegeberg et al. 2020), respectively.

Parameter	Key considerations	Warm Water Environment (Wenning et al. 2018)	Cold Water Environment (Wegeberg et al. 2020)
Temperature	Many oil properties and weathering processes are temperature dependent.	Higher degree of evaporation. Lower viscosity and thereby more easily surface spreading. Higher potential for w/o-emulsification which creates challenges for OSR. Exposure potential is high immediate post-spill and declines quickly with warm temperatures and rough seas as compared to colder water conditions.	Low degree of spreading and evaporation. Higher viscosity and thereby more reluctant surface spreading. A high viscosity oil will reduce the effectiveness of dispersant use and challenge conventional mechanical measures. Exposure potential tends to be prolonged because of slower evaporative processes.
Mixing energy	To disperse oil mixing energy is essential. Mixing energy is provided by wind / waves, but which are calmed by ice (Nuka and Pearson 2010).	High mixing energy potential. Tendency for high degree of emulsification, and oil can settle deeper in water column. Thus, exposure potential in the water column and food chain can be (spatially) significant, even in calm sea conditions.	Sea ice can limit the rate of mixing and spreading (IPECA 2015). Low mixing energy will reduce the effectiveness of chemical dispersant use. Slowed down oil weathering and hence a potential larger operational time window. Exposure potential in the water column and food chain can be limited during calm seas conditions (ice) due to low natural dispersion of the oil into the water column.

Table 3. Specific considerations on the effect of oil spills in relation to a temperate/sub-tropic (warm) and arctic (cold) water environment based on the CRA (Bock et al. 2018) and EOS tools input (Wegeberg et al. 2020), respectively.

Parameter	Key consideration	Warm Water Environment	Cold Water Environment
Valued Ecosystem Component (VECs):			
Key species in exposure assessment	Sentinel species in OSR assessments are those that may lead to cascade effects to other species; animals considered vulnerable and threatened; species with national and international social significance; as well as commercial, e.g., fish species.	For example, sea turtles, dolphins, and pelicans, commercial fish species (Bock et al 2018).	For example, bowhead whale, walrus, Greenland halibut, Northern shrimp, common eider, arctic copepod *Calanus hyperboreus*, capelin and polar bear (Christensen et al. 2016; Boertmann and Bay 2019).
Seasonality:			
VECs	From low to high latitudes differences between seasons become more profound in temperature and light conditions, which also leads to that occurrence of VECs may vary greatly between seasons.	High species richness year-round (Henriques et al. 2017) tends towards great year-round potential consequences to ecosystems and food chains.	The ecological consequences of a spill event can differ substantially in the summer vs winter seasons because of the migratory habits of avian, fish and marine mammal species (Boertmann et al. 2013). Also, hibernation of, e.g., the copepod *Calanus hyperboreus* in deep water during autumn and winter months leads to less exposure to spilled oil, also due to the lack of feeding activity through the hibernation period (Agersted et al. 2018).
Temperature	Differences in evaporation and viscosity of oil as a result of		Oiling of common eider feathers disrupt feather structure and result

Parameter	Key consideration	Warm Water Environment	Cold Water Environment
	temperature (Table 2) may affect the impact from organisms get oiled.		in reduced insulation (Fritt-Rasmussen et al. 2016). Effects of smother of an Arctic tidal macroalgae depend on oil type (Wegeberg et al. 2020).
Ice	Ice along the shore may catch and in cooperate oil to be released in spring (next season) (EPPR 2018), and hence increase persistence of the oil on the shore. Oil in ice may lead to oil being transported to other (unknown) locations Soot particles deposits on ice may reduce the reflective effect of ice, and hence lead to warming and melt of ice (reduced albedo effect).	Not relevant in warm water environments.	Highly relevant in Arctic environments.
Ecotoxicology:			
Toxicity and accumaulation	Toxic effects of oil on organisms may be lethal or sub-lethal or induce adverse effects on next generation, e.g., eggs, juvenile stages. Comparisons of Arctic and non-Arctic species exposures to petroleum hydrocarbons suggests few differences in potency and toxic response to exposure, although some species-specific	E.g., Stieglitz et al. (2016) demonstrated significant swim performance impacts on young adult mahi-mahi (*Coryphaena hippurus*) when exposed to crude oil.	E.g., Tairova et al. 2019 observed adverse developmental effects on the vulnerable early life stages of Arctic capelin. Storage of lipids for insulation and initiation of growth/ reproduction after hibernation because of strong seasonality may result in accumulation of oil compounds in, e.g., the lipid rich

Parameter	Key consideration	Warm Water Environment	Cold Water Environment
	differences are evident (French-McCay (2002).		Arctic copepod *Calanus hyperboreus* (Nørregard et al. 2015, Agersted et al. 2018), and lead to delayed adverse effects when lipid is metabolised.
Degradation	Degradation process of oil by bacteria may be temperature dependent.	It is anticipated that biodegradation rates are higher in warm waters as compared to colder water conditions based on a general temperature dependence, Q_{10}. The Q_{10} value is defined as the multiplier by which degradation rates increase with a 10°C rise in temperature. If oil degradation in Arctic marine environments follows the general trends for organic carbon turnover, the potential for oil degradation at low temperatures may be higher than previously anticipated, but this is only (1) if the microbial degraders are present in sufficiently high numbers, (2) if they are cold adapted, (3) if they have the metabolic capacity to degrade the multitude of structurally different compounds that are present in oil products, (4) if mineral nutrients are available and, finally, (5) if the bioavailability of oil compounds is not severely limited by the low temperature (Johnsen et al. 2018).	
Recovery time:			
	Recovery time is the time needed for a population to re-establish and depends on generation time and density of population after acute mortality.	Complex food webs in warm waters and species redundancy at different tiers can limit the ecological consequences of spilled oil and support shorter recovery times than in colder water environments (Haney et al. 2017, Keesing et al. 2018).	Recovery time may be long, for example, king eider population dynamics in Greenland indicate recovery may take several decades if mortality is comprehensive (Wegeberg et al. 2016).
Recruitment:			
	Recruitment is the potential for a species to re-establish after acute mortality and depend on, e.g.,	Complex food webs in warm waters and species redundancy at different tiers can limit the	Shorter food web chains in the Arctic may lead to severe cascade effects if a trophic level is

Parameter	Key consideration	Warm Water Environment	Cold Water Environment
	influx, re-colonisation and demography	ecological consequences of spilled oil and support shorter recovery times than in colder water environments (Huebert et al. 2018).	damaged and where recruitment is limited due to, e.g., low influx (Mosbech et al. 2018).

CONCLUDING REMARKS

The CRA and EOS assessment approaches are powerful tools for evaluating and developing oil spill response strategies appropriate to warm water and cold water environments, respectively. Both tools merge complex environmental and ecological information in to a framework useful to decision-making; further, both tools are sufficiently flexible to be applicable to a broader range of climatic conditions. The CRA and EOS tools are useful to identify OSR technologies, or combinations of OSR technologies, that can minimize the consequences on the environment from spilled oil. Research targeting environmental impact science and OSR technology improvements will enhance the predictive ability of CRA, EOS and similar OSR assessment models. Observations from pre-spill baseline studies and the knowledge gained from prior spill events is preferable for hypothetical modeling to defining different taxa representative of the aquatic life known or suspected to be present in different marine habitat compartments (e.g., open water, nearshore, seabed, and shoreline) and the impact, where spilled oil is expected to occur.

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