Deepwater Response Options - a Modelling Study Comparing Subsea Dispersant Injection and Mechanical Recovery using residual surface oil as a simplified effectiveness indicator.

Per Johan Brandvik[1], Jørgen Skancke[1], Ragnhild Daae[1], Kristin Sørheim[1], Per S. Daling[1],
Karina Heitnes Hofstad[2], Øystein Rantrud[2] and Thomas McKeever[3],
[1] SINTEF Ocean, Trondheim, Norway.
[2] Equinor Petroleum ASA, Norway.
[3]Equinor Canada Limited, St. John's, Canada

Abstract

The low oil recovery rates reported during Macondo (3-5% of the released oil) have caused discussions regarding the efficiency of mechanical recovery compared to other oil spill response options. These low recovery rates have unfortunately been used as reference recovery rates in several later modelling studies and oil spill response analysis. Multiple factors could explain these low rates, such as operational priorities, where dispersants and/or in situ burning are given priority before mechanical recovery; extended safety zones; availability of adequate equipment and storage capacity of collected oil; the number of units available; the level of training and the available remote sensing support to guide operations.

This study uses the OSCAR oil spill model to simulate a deep-water oil release to evaluate the effect of different response options both separately and in combination. The evaluated response options are subsea dispersant injection, mechanical recovery, and a combination of these.

As expected, Subsea Dispersant Injection (SSDI) was highly effective and resulted in a significant reduction in residual surface oil (8% of released oil volume, versus 28% for the non-response option, NR). However, using large offshore oil recovery systems also reduced residual surface oil with a similar amount (9% of released oil volume).

These results deviate significantly from the efficiency numbers reported after the Macondo incident and from later modelling studies scaled after the Macondo recovery rates. The increased efficiency of mechanical reported in this study is mainly due to inclusion of updated

descriptions of response capabilities, reduced exclusion zone, a more realistic representation of surface oil distribution and modelling of response units' interactions with oil, (efficient oil recovery only on thick parts of the oil slick).

The response capabilities and efficiency numbers for the different response options used in this study are based on equipment specifications from multiple response providers and authorities (Norwegian Clean Seas organisation (NOFO), Oil Spill Response (OSRL), Norwegian Coastal Administration (NCA), US Bureau of Safety and Environmental Enforcement (BSEE) and others). These capabilities are justified by well-established contingency plans, offshore exercises and annual equipment performance testing with oil.

Contact person: Per Johan Brandvik, PhD., Senior Scientist/Professor
SINTEF Ocean AS, Marine Environmental Technology, 4762 Trondheim, Norway.
Email: per.brandvik@sintef.no. Phone: +47 9095 8576

1 Introduction

The understanding of basic mechanisms and the efficiency and operational use of subsea dispersant injection (SSDI) has increased since the first large-scale use during the Deepwater Horizon oil spill in 2010. Since then multiple research programs have been performed focusing on fundamental processes like oil droplet formation (Brandvik et al., 2017, Nedwed, 2017), effect of dispersants (Brandvik et al., 2019), dispersant injection techniques (Brandvik et al., 2018) and in-situ measurements of reduction in oil droplet size or SSDI effectiveness (Davies et al., 2017). The main objective for a SSDI operation is to influence the fate and environmental effect of the oil from the subsea release by reducing the oil droplet sizes from multiple millimetres to a few hundred microns (average droplet size or d_{50}). This will reduce the amount of surfacing oil, but possibly, more importantly, change the distribution and lifetime of the surface oil slicks formed (Daae et al., 2018). SSDI is today established as an operative oil response option in several countries worldwide. Regions that earlier solely relied on mechanical recovery have now also implemented SSDI (Bluhm and Xirotyri, 2014).

Low efficiency, evaluated by recovered oil volumes compared to the total released oil volume (< 5%) was obtained for mechanical recovery during the Macondo oil spill in 2010 (Lehr et al., 2010). Multiple factors could explain these low rates, as for example; operational priorities, where dispersants and/or in situ burning were given priority before mechanical recovery; extended safety zones; availability of adequate equipment including storage capacity of recovered oil, number of available units for oil recovery, level of training and also available remote sensing support to guide operations.

Mechanical recovery has been the main response option on the Norwegian Continental Shelf (NCS) since the oil production started in the seventies. Surface dispersant application was added as a supplemental response option in the mid-nineties (Lunel et al., 1995, Brandvik et al., 1997).

SSDI has been implemented post-Macondo and are included in contingency plans as a safety measure to deflect oil and volatiles from responders during the work to cap a subsea blowout, and increasingly also evaluated as an oil spill response technology to reduce environmental impact. SSDI is assessed as an oil spill response option in Norway (Equinor, 2017, 2018), however NCS area is mostly a shallow water basin (below 300 meters water depths in most areas), and under these conditions SSDI is not considered very efficient in reducing oil amount reaching the surface. This is mainly caused by high gas to oil ratios giving sufficient buoyancy for the oil and gas plumes to surface. This is one of the reasons for SSDI not being broadly implemented as an oil spill response option in Norway, along with mechanical recovery and surface dispersants. In-situ burning has so far not been implemented as a contingency method in Norway and is for this reason not included in this study.

The offshore oil spill response capability on the NCS is organised by the Norwegian Clean Seas Association for Operating Companies (NOFO). NOFO is owned by the oil companies operating on the NCS and were established to ensure that Norwegian North Sea offshore operators complied with the authorities' oil spill contingency requirements for their offshore exploration and production (NOFO 2019, NOFO 2009, Jørgensen 2017 and Kristoffersen 2017).

The main motivation for this modelling study simulating a deep-water subsea release, was to compare different oil spill response options available on the NCS including:

- Large-scale mechanical recovery
- Surface dispersant application (by vessels and air
- Subsea dispersant injection (SSDI)

The response options are compared both individually and in various combinations. Remaining or residual surface oil (volume/area) after 30 days is used as a simplified measure when comparing response effectiveness. This paper presents only parts of this extensive study and focus on SSDI and large-scale mechanical recovery.

2 Methods

2.1 Oil Spill Modelling

In this study the OSCAR model (ver. 10) has been used to predict blowout plume behaviour, the fate of the oil and the effect of the different oil spill response options (Reed et al., 2000). OSCAR is a 3-dimensional model system that calculates and records the distribution, as mass and concentrations, of contaminants on the water surface, on shorelines, in the water column and in sediments. The model also calculates evaporation and biodegradation. For subsurface releases, such as blowouts or pipeline leakages, the near field part of the simulation is computed with a multi-phase integral plume model (Johansen, 2000, 2003) embedded in OSCAR. The near field model accounts for buoyancy effects of oil and gas, hydrocarbon dissolution, hydrate formation, and gas expansion as well as effects of ambient stratification and cross flow on the dilution and rise time of the plume.

Droplet size distribution due to turbulent break-up near the plume outlet is predicted using the Weber scaling method as described in Johansen et al. 2013, accounting for interfacial tension between oil and water, oil viscosity, flow rate and outlet dimensions. Subsea injection of dispersants is modelled in OSCAR by reducing the interfacial tension between the oil and water, leading to a reduced oil droplet size (Brandvik 2019).

OSCAR may compute oil weathering from crude assay data, although the most reliable results are produced if the target oil has been through a standardized set of laboratory weathering procedures established by SINTEF (Daling et al., 1990, Daling et al., 2014). In this case, oil data from an earlier weathering study of Oseberg Blend crude was used (Leirvik and Resby, 2007).

The OSCAR model also includes a module for oil spill response options. It is possible to describe both mechanical recovery, surface dispersant application and subsea dispersant injection with the use of this module. Surface dispersant application is possible to model using both vessels and aircrafts as platforms for application.

2.2 Environmental Data

OSCAR can utilise both 2 - and 3-dimensional current data from hydrodynamic models, and single point or gridded wind data from meteorological models. The simulations described in this study use timeseries of 2-dimensional wind and 3-dimensional current fields as described in this section.

SINMOD is a coupled 3D hydrodynamic and biological model system (Slagstad and McClimans 2005; Wassmann et al. 2006). The model is hydrostatic and produces results on a regular grid with square cells in the horizontal plane. In the vertical, the model uses z coordinates, where the upper layer and bottom layer in each cell vary with surface elevation and local depth, respectively, while the layers between the top and the bottom have constant depth. This means that there are different numbers of layers between grid cells due to the local water depth.

The primary input data sources for the model are bathymetry values for the model grid, atmospheric forcing fields, fresh-water run-off (from rivers or diffuse run-off) and boundary values. The model is typically run with a nested setup, where larger scale areas (e.g. in 20 km horizontal spatial resolution) provide boundary values for higher resolution areas covering a smaller area (e.g. 4 km horizontal spatial resolution). The dataset used in this project has a horizontal spatial resolution of 4 km and a temporal resolution of 2 hours.

The wind data used in the modelling is the same as was used as an input/boundary condition for the current model (data from ERA-Interim, a global atmospheric reanalysis dataset). This means that the wind and current are coupled. In the full project report (Daae et al., 2019) the modelling was performed for two different 30-day periods (autumn and spring), corresponding to a medium wind (2 - 10 m/s) and a strong wind period (5 - 15 m/s). Only results from the medium wind period are presented in this paper. Results from the full study are available in the technical report (Daae, et al., 2019).

2.3 Release Scenario

The location and conditions selected for this study are representing a generic deep-water release and is not intended to represent any specific oil field. The oil type is a light paraffinic crude represented by Oseberg blend (Leirvik and Resby, 2007). The release conditions are given in Table 1. Relevant modelling of the oil temperature and viscosity during droplet formation is highly important, since the droplet sizes formed is highly sensitive to oil viscosity, especially at low interfacial tension (IFT) (Johansen et al., 2013).

Table 1: Release conditions

Parameter	Value
Location	71° N, 0° E
Release depth	2 000 m
Duration	30 days
Oil rate (no water fraction)	8 000 m^3/day for 30 days
Gas to oil ratio (GOR)	200 Sm^3/m^3
Gas density	0.8 kg/Sm^3
Oil density	0.839 kg/L
Release diameter	25.4 cm
Volume fraction of gas at release depth	0.6
Adjusted release velocity*	4.1 m/s
Oil type	Oseberg Blend 2006
Oil viscosity at release (gas saturated)	0.7 cP (80 °C/shear rate 10 s^{-1})
Oil IFT (untreated)	15.5 mN/m

*: Adjusted for gas fraction and Freud number according to Johansen et al., 2013.

2.4 Definition of Scenarios

A response scenario in this study is a combination of individual response methods, specifying the number of units, response times and strategies (priorities/exclusion zones). The first scenario is the No-Response (NR) case, defined in the previous section and used as a baseline or reference case for all the other scenarios. The second scenario is a large-scale mechanical recovery operation (MR), followed by subsea dispersant injection (SSDI) scenario and the last scenario is a combination of these two (MR and SSDI). An overview of the scenarios is presented in Table 2. In the complete study, totally 13 scenarios were modelled, see the technical report (Daae et al., 2019) for further details.

Table 2: Identities for the different scenarios used in this modelling study

Scenario number	Description
1	NR: No response - Baseline scenario.
2a	MR: Mechanical recovery - 8 high capacity NCS recovery units.
3	SSDI: Subsea dispersant injection - Modified OSRL dispersion kit.
5a	SSDI+MR: Combined approach - SSDI + 5 high capacity NCS recovery units.

The descriptions of the individual response methods are based on specifications from oil spill response associations like NOFO (NOFO 2019) and OSRL (OSRL 2018) or governmental authorities like the Norwegian Coastal administration (NCA 2018) and BSSE (BSEE 2017, Hamilton 2016, Caplis et al., 2017). The specifications used are, as far as possible, documented by results from offshore testing of the response technology. Offshore experiments with oil have a long history in Norway. In the past (1975 – 2000) these field trials were used to study more fundamental processes (oil drift and spreading, oil weathering processes, use of dispersant, in-situ burning, oil-in-ice, subsea releases), but lately (2000 – 2019) these field trials have focused more on development and verification of oil spill technology. A review of the outcome of these field trials can be found in Faksness et al., 2016. Several of the response options in the present work involve multiple units, for example offshore vessels that are operated continuously for 30 days. The modelling assumes sufficient personnel resources onboard for continuous operation and that additional vessels are standby for replacement if needed.

The specifications for different response options (efficiency and constraints) are not identical in the different sources listed above and to harmonise and make sure that the modelling results are on the conservative side some of the specifications used in this study are lower than what can be found in the sources. The vessels used for mechanical recovery are standard standby and supply vessels used on the Norwegian Continental Shelf (NOFO 2019). For the SSDI scenario, the logistical support was based on national stockpiles available in Europa (European Maritime Safety Agency, EMSA 2016) and worldwide (OSRL 2017). Relying on these stockpiles, availability of dispersants was not regarded as a limiting factor for the modelled 30-day operation.

2.4.1 Subsea Dispersant Injection (SSDI)

Dispersants were assumed injected into the oil coming out of a vertical pipe (for example the blow-out-preventer) within a few release diameters before the oil was released. This allows the dispersant to be injected into a compact cone of oil, mixed with the oil, reducing interfacial tension before the oil droplets are formed in the highly turbulent zone immediately after the release (Brandvik et al., 2018). Applying the dispersant directly into the well-stream has operational advantages compared to spraying dispersant on a weathered and scattered surface oil slick with respect to; application success, mixing of oil and dispersant, oil viscosity and turbulence available for droplet formation.

The modelling assumes use of equipment for dispersant dosage control and monitoring of oil droplet sizes, to optimize the dispersant injection (Brandvik et al., 2020). The elevated temperature of the gas saturated live oil could give a low initial viscosity (< 1 cP). A dispersant dosage of 2% is expected to give an IFT of 0.3 mN/m for light paraffinic oil types that Oseberg represents (Brandvik et al., 2019), resulting in a tenfold reduction in oil droplet sizes (d_{50}) from 3.8 mm to 0.37 mm, see Table 3. The theoretical rising time (Stoke law rising velocity in static water) from 1200 meters depth (the modelled plume trapping height, see Figure 1 and Figure 2) are less than an hour for the large droplets (3.8 mm) without any treatment, versus 35 hours for the smaller droplets after dispersant injection (0.37 mm). However, the modelled rising times for the small droplets resulting from SSDI were significantly higher due to turbulence in the upper water levels. This increase in rising time for the small treated oil droplets strongly influences the fate of the released oil in the marine environment, causing reduced amount of oil to reach the surface. The surfacing oil will usually cover a large area due to the reduced rising time and increased spreading of the small droplets. However, the oil slicks formed when the oil droplets reach the surface are usually very thin with a short lifetime. The SSDI scenario (scenario 3) was simulated in OSCAR by modelling a release similar to Scenario 1, with No Response for the first 5 days, then reducing the oil droplet sizes as described in Table 3.

Table 3: Definition Response scenario 3: Subsea Dispersant Injection (SSDI)

Period (day)	**SSDI**	**d_{50} (µm)***
0-5	No	3 803
5-30	Yes	373

* d_{50}: Median volume oil droplet size

2.4.2 Mechanical Recovery (MR)

The MR efficiency is mainly determined by the volume of oil available for the booming operation, the size of exclusion zone, boom characteristics (wave tolerance and boom leakage), oil properties and weather conditions. For these reasons, a realistic description of surface oil distribution, oil thickness and the interaction with skimming units (recovery of thick oil) is important. Using an average oil film thickness to calculate encounter rate (area swept per hour) will significantly underestimate effectiveness of mechanical recovery. However, many response calculators and oil response models use this principle. Modelling sweeping operations covering large areas with a calculated average oil film thickness, is not very operationally relevant and give very low effectiveness.

Mechanical recovery is in this study simulated by modelling the interaction between the drifting oil and the individual response units. The number of units, their specifications and mobilisation time are selected from existing oil spill contingency analyses for the Norwegian continental shelf (for example Equinor, 2017), see

Table 4.

Internal tank capacity of the skimming vessels, the distance to offloading barges, cruising speed and transfer time are also important parameters, especially for long term response operations, as described in this study. This study is based on state-of-the art offshore equipment, standard on the Norwegian continental shelf and operative in many other countries and regions. Two different types of booms were simulated:

1. A large boom system with a swath width of 185 meters towed at a traditional 0.7 knots (NOFO 2019), in this study called a passive system and
2. Active systems with a higher towing speed due to «sweeper panels» of deflectors that reduce the relative surface current speed and concentrate oil into a «recovery channel» with an integrated skimmer (NOFO 2019).

These large offshore systems can tolerate higher waves (3.5- and 2.5-meters significant wave height), however, the modelled boom leakage increases at higher sea states. The active systems were usually used further away from the surfacing site due to its enhanced speed and manoeuvrability. A total of eight systems were mobilised over a seven-days period. Five of the offshore systems were equipped with remote sensing resources being able to perform night operations (operate 24 hours a day), with a 65% efficiency at night, see

Table 4 and the technical report (Daae et al., 2019) for further details.

Table 4: Definition of Scenario 2: Large-scale mechanical recovery (MR)

	Vessel #					
	1	**2 & 3**	**4**	**5**	**6**	**7 & 8**
Mobilisation time (hr)[1]	1	72	168	168	168	168
Transfer time to external tanker (hr)[2]	6	6	6	6	6	6
Operation at night (%)[3]	65	65	65	0	65	0
Strategy[4]	Newest	Newest	Newest	Newest	Newest	Newest
Exclusion zone (m)[5]	2000	2000	2 000	2 000	3 000	3 000
Cruise speed (knots)	14	14	14	14	14	14
Tank capacity (m^3)	1 500	1 500	1 500	1 500	1 500	1 500
Swath width (m)	185	185	185	185	50	50
Maximum operational wave height (m) [6]	3.5	3.5	3.5	3.5	2.5	2.5
Operational speed during recovery (knots) [7]	0.7	0.7	0.7	0.7	2.5	2.5
Efficiency (%)[8]	80	80	80	80	80	80
Skimming capacity (m^3/h) [9]	200	200	200	200	100	100
Threshold/film thickness (mm) [10]	0.1	0.1	0.1	0.1	0.1	0.1

1: Total time before resource is available at spill site.
2: Time needed to transfer recovered oil to external tanker (cruise time to tanker excluded).
3: Units with remote sensing support (IR camera in balloon or onboard oil radar). Night effectiveness 65% (12 hours).
4: Option for oil targeted by recovery units (Thickest, Newest, Closest, Oldest) in OSCAR response module.
5: Circular exclusion zone around release position.
6: Significant wave height where boom effectiveness is assumed zero (complete boom leakage), see Daae et al., 2019
7: Maximum towing speed relative to surface currents (active/passive)
8: Maximum booming efficiency in calm water (20% leakage of oil volumes entering boom system assumed)
9: Maximum skimmer capacity. However, oil volumes collected in the boom system were usually capacity limiting, not skimmer capacity.
10. Minimum oil film thickness for skimmer operation (water free oil thickness).

The search strategy for surface oil slicks in the OSCAR response module was set to target the newest combatable oil, which mean that the mechanical recovery units usually keeps their position close to the exclusion zones. This strategy gave the most effective oil recovery.

2.5 Positioning of Response Resources

Finding the optimal position for response operations relative to the spill site is often an evaluation of many factors, taking health and safety for personnel into account and at the same time have access to relatively fresh, thick, and concentrated layers of oil. To reduce oil spill responder's exposure to volatile components and reduce risk of explosion hazard it is advisable to let the oil weather on the surface for a while to allow the lightest components to evaporate. Leakages of oil under the boom will also be reduced when oil viscosity increase due to weathering (evaporative loss and emulsification). The oil spill contingency plans on Norwegian Continental Shelf usually refer to a flash point above sea temperature (reduced explosion hazard & human exposure) and a viscosity of 1 000 cP (13 °C, at shear rate 10 s^{-1}) to reduce boom leakage (Nordvik et al 1992). For a light paraffinic oil like Oseberg Blend, this usually corresponds to a weathering time of 1-2 hours or a safety distance of 1-3 km. In this study we have used an exclusion zone of 2 km and operate response equipment at approximate 2 - 5 km from the estimated centre of the surfacing oil.

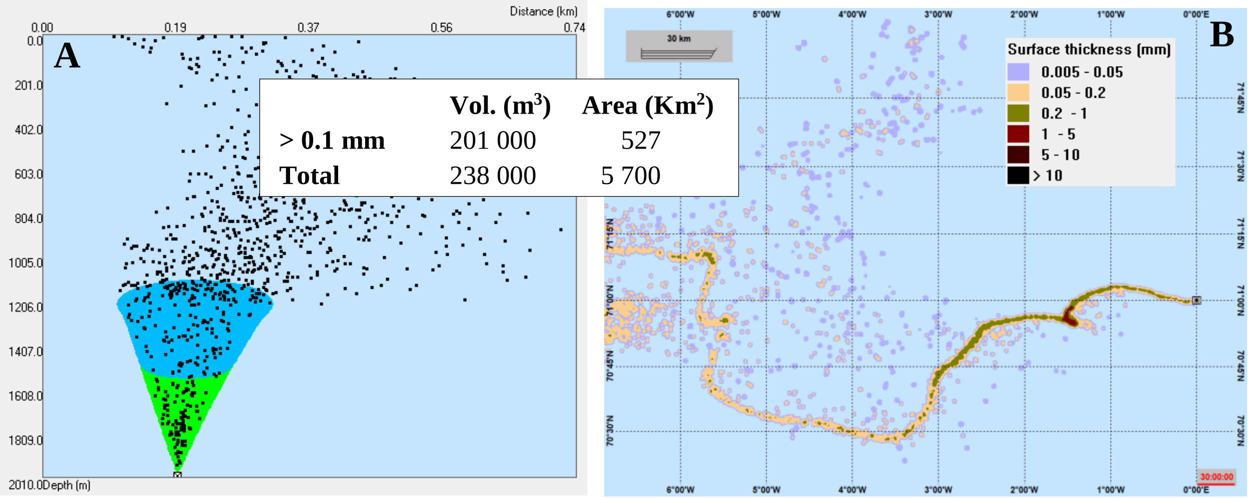
3 Presentation of Modelling Results

The following sections describe the results from the scenarios presented in Table 2 with focus on surface oil distribution (volume and area covered). Initially the results for the No-response scenario is presented and then results on how the response options have reduced both surface oil volume and area are presented. The volume and area of oil remaining on sea surface after 30-days are used as a measure of response effectiveness in this study.

More complete mass balances including evaporated-, surfaced-, recovered-, dispersed-, biodegraded- and submerged oil are also presented when comparing oil spill response effectiveness of all the scenarios (see Figure 6 and Figure 7).

3.1 No Response Scenario (NR)

The condition for the release is presented in Table 1. Model results show that the plume of released oil, gas and entrained water lost buoyancy and was trapped at around 1200 m depth (Figure 1A). From this depth, oil droplets were transported towards the surface, as a function of droplet size and oceanographic condition. The trapping depth is mainly determined by the buoyancy imparted by the gas and its gradual dissolution. Since the gas release rate was similar for all scenarios the trapping depth was also similar for all scenarios. The large untreated oil droplets (d_{50}: 3.8 mm) surfaced within 4.5 hours and formed a concentrated surface oil slick, see Figure 1.



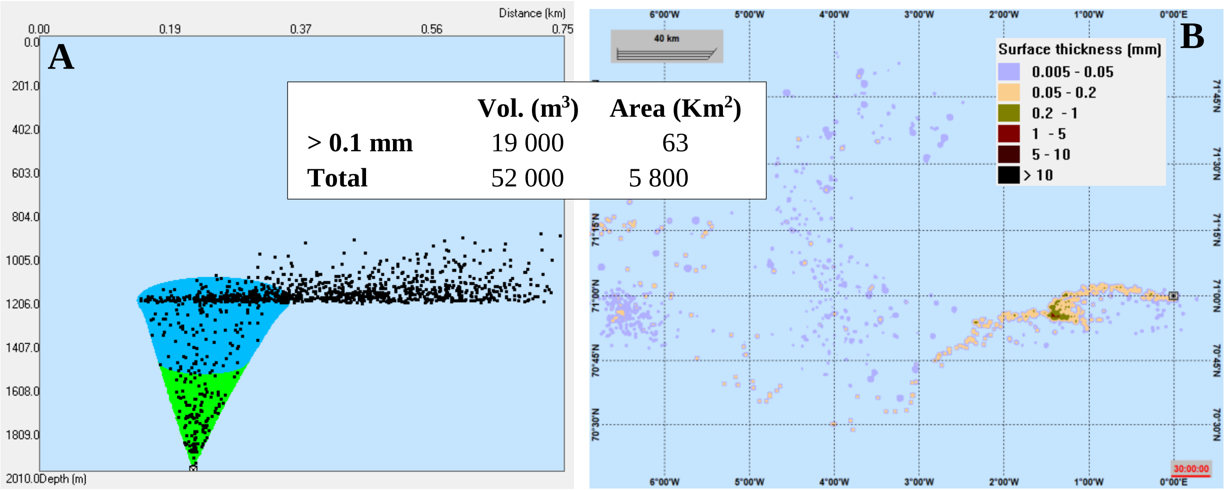
	Vol. (m^3)	Area (Km^2)
> 0.1 mm	201 000	527
Total	238 000	5 700

Figure 1: A: The plume was trapped at approx. 1200 meters depth for all scenarios, releasing the oil droplets surfacing as a function of droplet size and oceanographic conditions. B: Distribution of surface oil after 30 days of the No Response scenario (NR). Total volumes and areas of emulsified surface oil after 30 days in the inserted text box.

After 30 days, with a continuous release of oil, 527 km^2 of sea surface is covered with thick oil (> 0.1 mm) adding up to 201 000 m^3 of emulsion. The total oil covered area (5 700 km^2) is more than ten times larger but contains only about 20% more oil. Since the lifetime of thinner oil slicks, especially the sheens, is very short due to natural dispersion, the volume and area of thick emulsified surface oil (> 0.1 mm) are used to compare the effectiveness of different response options.

3.2 Subsea Dispersant Injection Scenario (SSDI)

The condition for the release and the SSDI response is presented in Table 3.



	Vol. (m^3)	**Area (Km^2)**
> 0.1 mm	19 000	63
Total	52 000	5 800

Figure 2: A: Illustration of the plume trapped at 1200 meters depth, releasing the oil droplets surfacing as a function of droplet size and oceanographic conditions. B: Distribution of resulting surface oil after 30 days of the subsea dispersant injection scenario (SSDI). Total volumes and areas of emulsified oil after 30 days in the inserted text box.

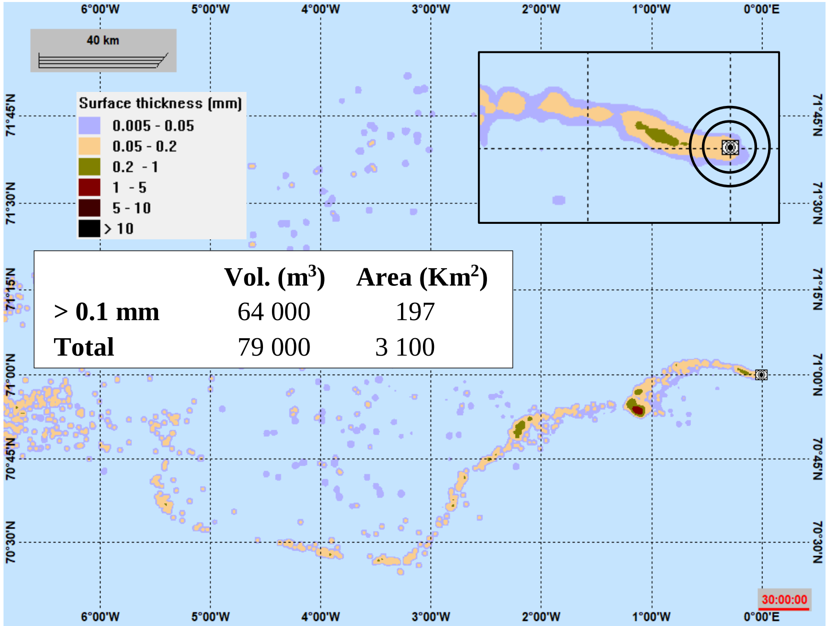
After 30 days, with a continuous release of oil and SSDI starting after 6 days, the surface area of thick emulsified oil (> 0.1 mm) is reduced to 63 km^2 adding up to 19 000 m^3 of emulsified oil. This is a large reduction in both surface oil volume and area, both being reduced to 10-12% compared to the NR scenario (thick oil > 0.1 mm).

The total oil covered area including sheen is approximate ten times larger. The total oil covered area is slightly larger (2%) than the NR scenario after 30 days. This is caused by the 10-fold reduction in oil droplets during SSDI (d_{50}= 373 µm) making the oil surfacing over a significantly larger area.

3.3 Mechanical Recovery Scenario (MR)

The oil spill response resources used in the large-scale MR scenario are described in

Table 4 and consists of eight standby and recovery vessels. The eight vessels have a mobilising time between 1 hour (standby vessel onsite) to 7 days, and their exclusion zones of 2 000 and 3 000 meters are indicated in Figure 3.



	Vol. (m^3)	Area (Km^2)
> 0.1 mm	64 000	197
Total	79 000	3 100

Figure 3: Distribution of surface oil after 30 days of release for the Mechanical recovery scenario (MR). The zoomed-in image indicates the dimensions of the main surface slick and the exclusion zones used in all scenarios. Total volumes and areas of emulsified oil after 30 days are reported in the inserted text box.

Recovered oil for the eight units, both as a function of time and at the end of the 30-day period, is presented in Figure 4. The figure shows a wide span in skimming effectiveness as a function of exclusion zone (access to thick oil), mobilisation time (hours in operation), unit specifications (wave tolerance and skimming speed) and remote sensing support (increased night operation effectiveness). The standby vessel with oils spill response equipment located on site (Unit 1, 1-hour mob time) has remote sensing capabilities (oil detection radar) and has also the highest total recovered oil volume (approx. 15 Kt water free oil), while the three units with the longest mobilisation time and no remote sensing support (dotted lines) have significant lower recovered oil volumes (4-5 Kt water free oil). The three active units have higher skimming speed, 2.5 knots (green lines). One of the active units is supported with remote sensing equipment (Unit 6, green solid line) and show a significant higher recovered volume (approx. 10 Kt waterfree oil) than the other units (similar response time), due to the ability to operate at night, although with 65% efficiency (Unit 4-8).

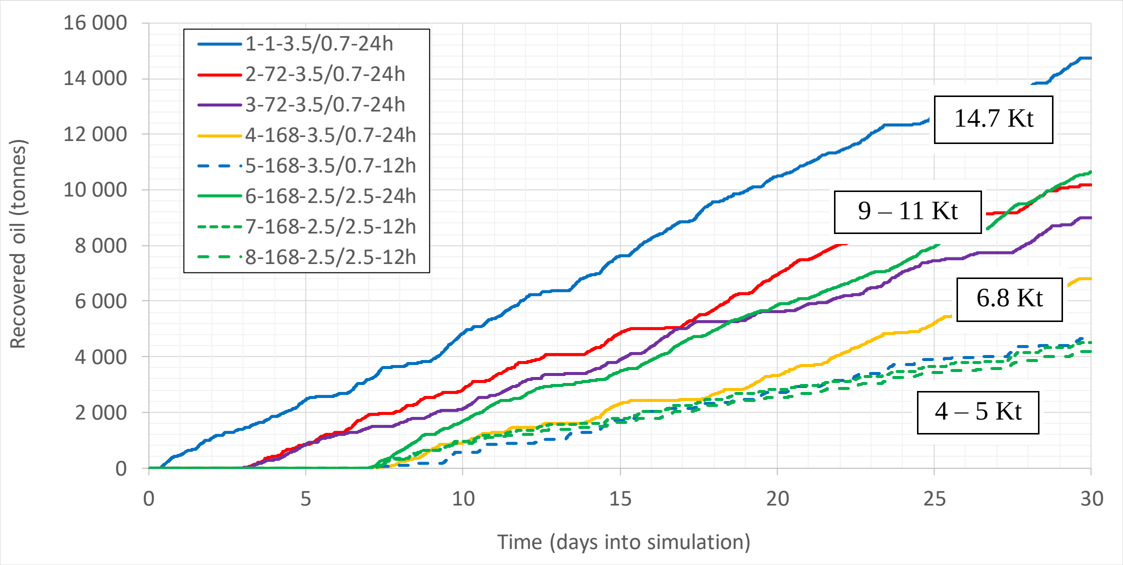


Figure 4: Volume of recovered water free oil for the eight units used for the Mechanical Recovery scenario (MR). Presented as a function of time (graphs) and total volume recovered for each unit after 30 days (numbers in brackets). A total of 63 Kt was recovered.

After 30 days with a continuous release, the sea surface area covered with thick oil (> 0.1 mm) is reduced to 197 km^2 which corresponds to 64 000 m^3 of emulsified oil, see Figure 3. This represent a reduction to 37% of the surface area and 32% of the oil volume compared to the NR scenario.

3.4 Combined Response SSDI-MR

SSDI is used as the primary response strategy in this combined scenario, supplemented with mechanical recovery, including 1 passive and 4 active units (correspond to unit 1 (passive) and 6 (active) in

Table 4).

The effect of the dispersant injection is very similar to what is described for the SSDI scenario. For this combined response, the volume and area of surface oil (> 0.1 mm) is significantly reduced (oil volume is 3% and surface area is 4% of the NR scenario). The surfacing oil is mainly thin oil films covering a larger area due to the ten-fold reduction in droplet size and increased rising time.

To increase the recovery effectiveness of the thinner oil films, slightly smaller boom systems that can operate at a higher towing speeds (2.5 vs. 0.7 knots), but reduced wave tolerance are used. These systems use weir skimmers, which should be unaffected by changes in oil properties (e.g. interfacial tension) due to subsea dispersant injection. The amount of recovered oil is strongly influenced by the effect of the SSDI on the surface oil (less oil spread over larger areas forming thinner oil films). Figure 5 shows a higher recovery rate the first 7 days for unit 1 (500 tonnes/day) until SSDI dominates the surface distribution of the oil after 7 days (wider/thinner films) with a consequence of lower oil recovery rate (70 tonnes/day). We also observe from Figure 5 that oil recovery was suspended during day 20-25 due to high waves, but increased significantly during the last 5 days due to good weather conditions, see Daae et al., 2019 for further details.

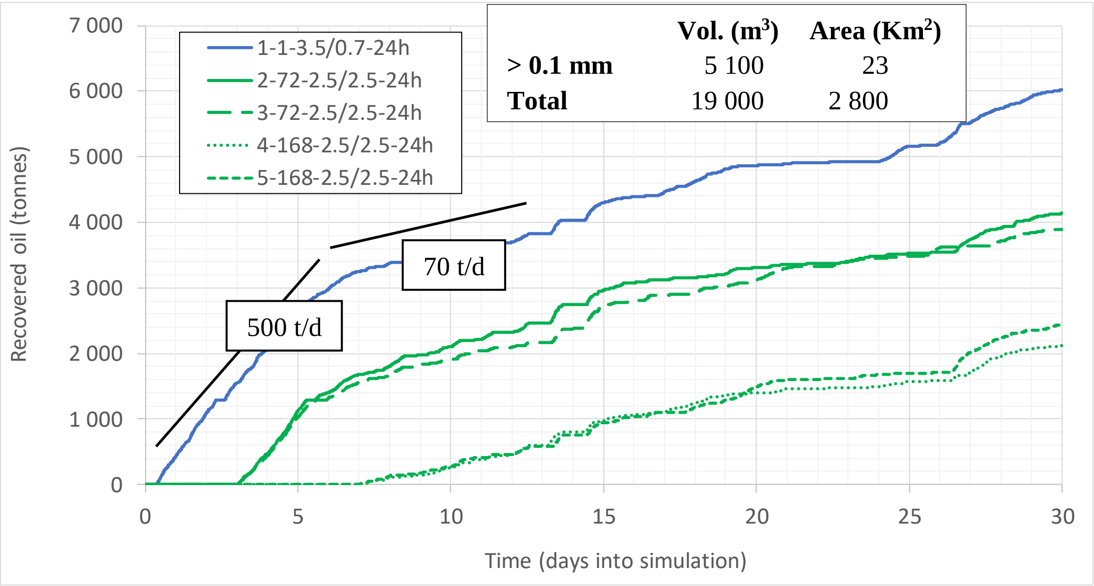


Figure 5: Recovered water free oil as a function of time for the combined scenario with Subsea Dispersant Injection and Mechanical recovery (SSDI-MR). Recovery rates (tonnes/day) are reported for day 1-6 and 7-14. Total volumes and area of emulsified oil after 30 days are reported in the text box.

After 30 days the sea surface area covered with thick oil (> 0.1 mm) is reduced to 23 km^2 corresponding to 5 100 m^3 of emulsified oil. This is approximately only 3% of the surface volume compared to the NR scenario and 25% of the surface volume compared to the SSDI scenario. Approximately a third of the oil was recovered during the first week, before SSDI was initiated.

4 Comparison of All Scenarios

To summarise the main findings from this modelling study the results from the NR scenario are compared to both the single response scenarios (MR, SSDI) and a combination of those. The water free oil mass balances as a function of time (30 days) at the end of the 30-day period are presented in Figure 6 and Figure 7. Note that figures showing area and volume related to thickness of surface oil (Figure 1 to Figure 5) are based on emulsified oil, while figures showing the summary mass balances use water free oil (Figure 6 and Figure 7). The mass percentages of surface oil in Figure 6 and Figure 7 do not reflect the large difference in surface oil thickness between the scenarios. This imply that the surface lifetime of the remaining oil after MR (9%)

can be significantly larger than the remaining oil on the surface after SSDI (8%), due to the oil being present as thicker and emulsified surface oil in the MR scenario.

Figure 6 clearly shows for all scenarios that the mass balances and fate of released oil is influenced by the weather conditions. The fraction of surface- (dark blue) and dispersed oil (light blue) is heavily influenced by wave induced redispersion of the surface oil. This is most clearly seen in the NR scenario, but the same trend with an increased fraction of dispersed oil during a high sea state between day 14 and 24 is observed for all scenarios. Another common feature is the high fraction of dispersed oil in the initial phase, which is reduced as the fraction of oil in the different compartments stabilise (NR) or is more influenced by the oil spill response operations.

The difference in "biodegraded oil" is not very noticeable between the scenarios. A larger difference with increased biodegradation for the small oil droplets created as a result of SSDI would be expected if the modelling period had been extended beyond the day 30 of the release.

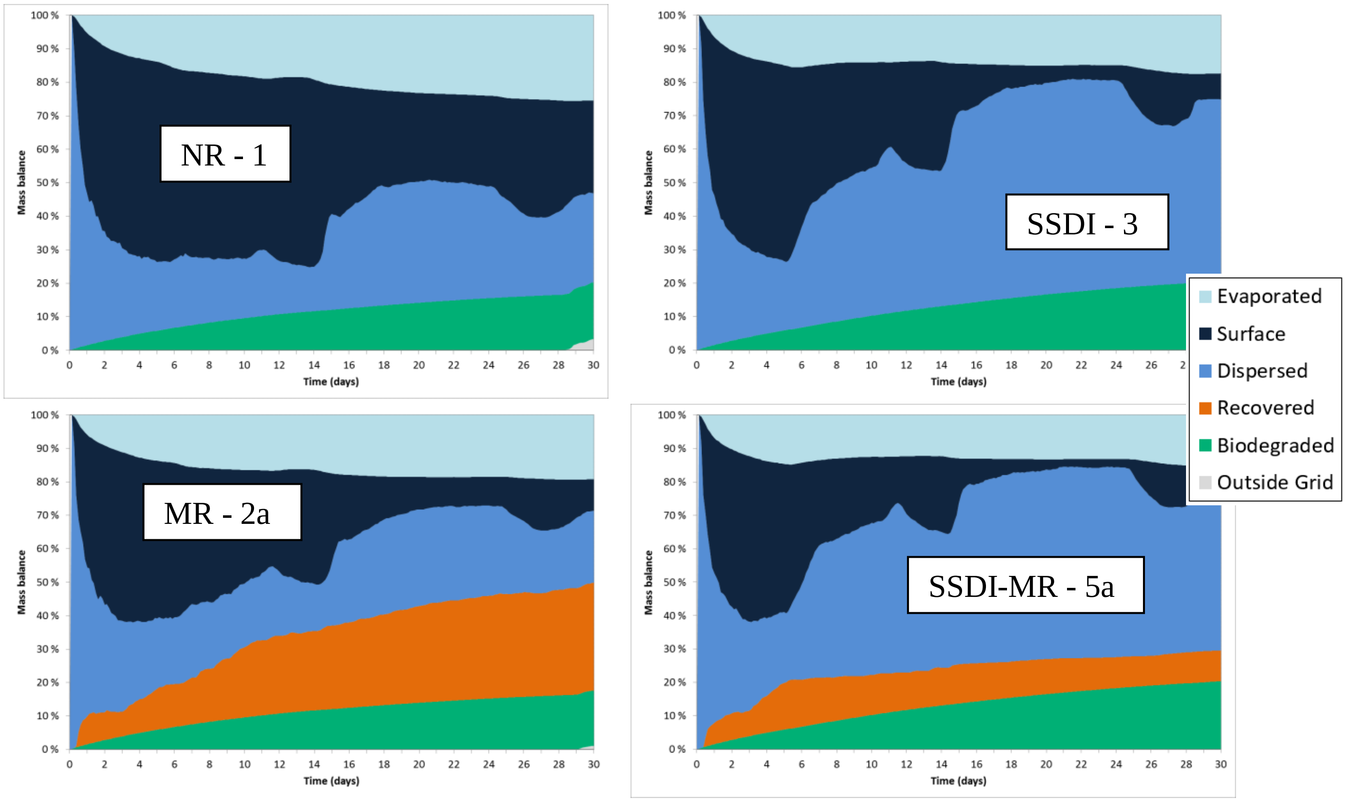
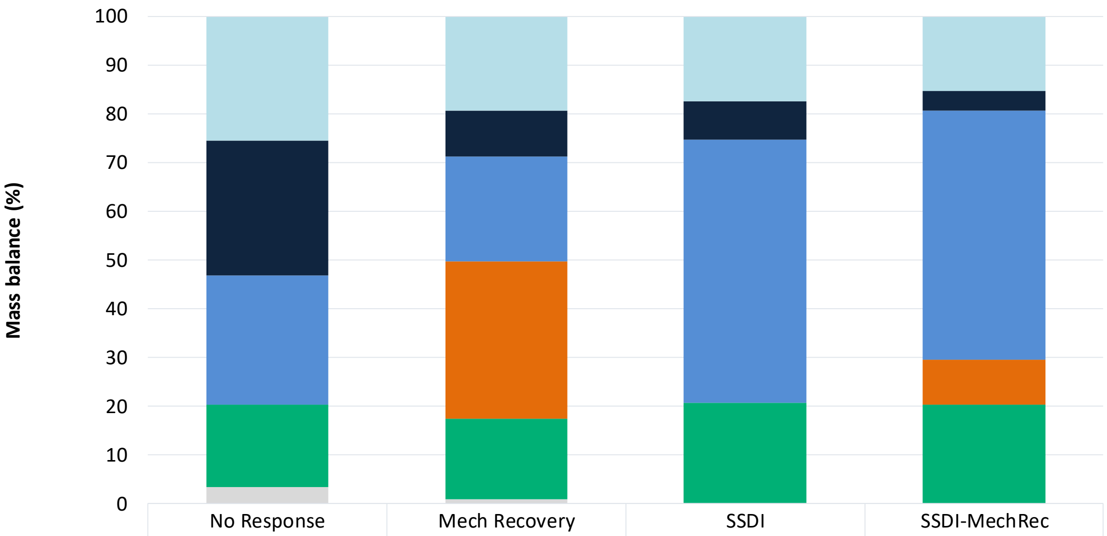


Figure 6: Mass balances versus time for all presented scenarios (water free oil).



	No Response	Mech Recovery	SSDI	SSDI-MechRec
■ Evaporated	25	19	17	15
■ Surface	28	9	8	4
■ Dispersed	27	22	54	51
■ Recovered	-	32	-	9
■ Biodegraded	17	17	21	20
■ Outside	3	1	0	0

Figure 7: Mass balances at the end of the 30-day period for all scenarios (water free oil).

As earlier stated, the effectiveness of the different scenarios is evaluated based on the amount of residual surface oil at the end of the 30-day modelling period. Figure 7 presents the mass balance (weight%) of the oil for all scenarios after 30 days. Judged by the residual surface oil volume (dark blue), SSDI gives a very high performance (8% remaining surface oil compared to 28% for NR), closely followed by mechanical recovery (9% remaining surface oil compared to 28% for NR). All percentages are compared to total oil volume release over 30 days.

The high effectiveness of SSDI in reducing surface oil volumes from a deep-water subsea release was expected and corresponds well with results from other studies (French McKay et al 2018, Daae et al., 2019, Makatounis et al., 2018). The results show that the amount of oil being dispersed as small droplets in the water column (light blue) are generally doubled compare to the NR scenario. This is both due to small droplets created by the subsea dispersant injection and the increased natural dispersion of the thin surface oil slicks.

The main findings in this study that deviates most from previous published results, are the high effectiveness's for scenarios relaying on mechanical recovery. Previous modelling studies show a very limited reduction in surface oil volumes and total recovered volumes (compared to the amount of released oil) of only a few percent (French McKay et al 2018). The main reason for the low effectiveness reported in these studies is that they have used the Macondo experience (5% recovered, Lehr et al., 2010) as state-of-the-art and a starting point and reduced the recovered volume due to threshold values for waves, currents and daylight. In such modelling studies, mechanical recovery in areas, close to the release, with higher oil thickness were not prioritized. Simulating oil recovery over large areas, based on an assumption of average oil film thicknesses (down to 0.008 mm) is not very operationally relevant and gives very low effectiveness for mechanical recovery.

There are probably multiple, reasons for the low effectiveness of mechanical recovery during the Macondo oil release. These could include; operational priorities (dispersants and/or in situ burning were given priority before mechanical recovery), extended safety zones, availability of adequate equipment including storage capacity of recovered oil, number of available units for oil recovery, level of training and also available remote sensing support to guide operations.

The approach used in this study for modelling of mechanical recovery includes:

- Response units available at the NCS are described with realistic properties (skimming/storage/offloading capacities, wave tolerance, towing speeds….).
- Numbers of units and response times are from existing NCS oil spill response plans.
- Realistic distribution of surface oil slicks, with thick layers of emulsified oil, not based on average oil film thicknesses.
- Modelling interaction between response units and thick layers of oil.
- Prioritise areas for recovery based on oil avaiability with a realistic thickness threshold (>0.1 mm).

5 Conclusions

The remaining surface oil (mass% of water free oil) after 30 days of continuous subsea release, was used as a simplified measure of response effectiveness for three different scenarios:

1. Using SSDI alone showed a very high response effectiveness (8% remaining oil compared to total oil volume released, versus 28% for the NR scenario).
2. The effectiveness increased when SSDI was used in combination with a reduced mechanical recovery effort (4% remaining oil compared to total oil volume released).
3. Large-scale mechanical recovery with multiple offshore units gave efficiencies comparable to SSDI (9% remaining oil compared to total oil volume released).

This study shows that mechanical recovery could offer a high response effectiveness on an offshore deep-water blowout if:

- Sufficient response resources are available close to the actual location (1 – 176 hours response time) and can be allocated to the operation (in this case, 8 offshore units).
- Equipment must be relevant for offshore use.
- Nearby Offshore offloading of recovered oil must be available.
- Reduced safety zones, to get access to thick continuous oil slicks.
- Remote sensing resources must be available (in this case five oil radar units).
- Sufficient personnel and equipment for 24/7 operation must be available.
- Weather conditions are within the operational range for the equipment and participating vessels.

The main weakness or uncertainty in this modelling study relaying on a large-scale mechanical recovery operation is the lack of ability to fully describe the complexity of such an operation. Limited extra time or extra response resources have been allocated for "downtime" due to equipment failure during the 30-day period. The modelling also assumes that extra recovery units and vessels are on standby for replacement if needed.

6 Acknowledgement

This modelling study was funded by Equinor ASA under contract 4590096693

7 References

Bluhm B., and Xirotyri, L.: 2014: What has Europe learned after the Deepwater Horizon/Macondo Incident?. International Oil Spill Conference Proceedings: May 2014, Vol. 2014, No. 1, pp. 348-360

Hamilton, B.A., 2016: BSEE Oil Spill Response Equipment Capability Analysis. https://www.bsee.gov/site-page/worst-case-discharge-scenarios-for-oil-and-gas-offshore-facilities-and-oil-spill-response.

BSSE 2016: Bureau of Safety and Environmental Enforcement, Genwest, Systems, Inc., 2016, Estimated Recovery System Potential (ERSP) Calculator and User Manual. https://www.bsee.gov/what-we-do/oil-spill-preparedness/response-system-planning-calculators.

Brandvik, P.J., Lewis, A., Daling, P.S., Strøm-Kristiansen, T. and Larsen, E., 1997: "On-land and offshore testing of a new helicopter bucket for dispersant application - Response 3000D". In Proceedings from Arctic Marine Oil Spill Program (AMOP), Environment Canada, Canada, pp. 499-519, 1997.

Brandvik, P.J., Johansen, Ø., Leirvik, F., Farooq, U., Daling, P.S., 2013. Droplet breakup in subsurface oil releases--part 1: experimental study of droplet breakup and effectiveness of dispersant injection. Mar. Pollut. Bull. 73, 319–26. doi:10.1016/j.marpolbul.2013.05.020

Brandvik, P.J., Ø. Johansen, E.J. Davies, F. Leirvik; D.F. Krause, P.S. Daling, D. Dunnebier, S. Masutani, I. Nagamine, C. Storey, C. Brady, R. Belore, T. Nedwed, C. Cooper, A. Ahnell, O. Pelz, and K. Anderson. Subsea Dispersant Injection - Summary of Operationally Relevant Findings From a Multi-Year Industry Initiative. SPE-179401. In proceedings from SPE HMS Conference Stavanger, Norway, April, 2016.

Brandvik, P.J., Johansen, Ø., Leirvik, F., Krause, D.F. and Daling, P.S. 2018: Subsea Dispersants Injection (SSDI), Effectiveness of Different Dispersant Injection Techniques – An Experimental Approach. Mar. Pollut. Bull. Volume 136, (2018), pp. 385-393.

Brandvik, P.J., Daling, P.S., Leirvik, F. and Krause, D.F. 2019: Interfacial tension between oil and seawater as a function of dispersant dosage. Mar. Pollut. Bull. Volume 143, (2019), pp. 109-114.

Brandvik P.J., Krause, D.F., Leirvik, F., Daling P.S., Owens, Z., Gilman, L., Yun, M., Ahnell, A. Carlsen, T., Koranek, M. 2020: Subsea Mechanical Dispersion (SSMD) a Possible New Option for the Oil Spill Response Toolbox?. In proceedings from International Oil Spill Conference 2020. New Orleans, USA.

Caplis, J., Krieger, A., 2017, The Next Generation of Planning for Offshore Oil Spill Response, 2017 International Oil Spill Conference Proceedings. https://www.bsee.gov/site-page/worst-case-discharge-scenarios-for-oil-and-gas-offshore-facilities-and-oil-spill-response

Daae, R.L., Brandvik, P.J., Skancke, J. and Sørheim, K.R, 2019: Data report from Response Options for an Offshore Deep-Water oil & gas release. SINTEF report 302004083, Trondheim, Norway.

Daae, R.L., Skancke, J., Brandvik, P.J. and Faksness L.-G. 2018: The sensitivity of the surface oil signature to subsurface dispersant injection and weather conditions. Mar. Pollut. Bull. Volume 127, (2018), pp. 175-181.

Davies, Brandvik and Leirvik 2017: The use of spectral transmittance imaging to size and classify suspended particulate matter in seawater. Mar. Pollut. Bull. 2017, vol. 115 Issue 1-2 pp. 402 - 410.

Nordvik, A. B., Daling, P. and Engelhardt, F. R. 1992. "Problems in the interpretation of spill response technology studies." In: Proceedings of the 15th AMOP Technical Seminar, June 10-12, Edmonton, Alberta, Canada, pp. 211-217.

Daling, P.S., Brandvik, P.J., Mackay, D. and Johansen, Ø., 1990: “Characterization of crude oils for environmental purposes”, in Proceedings from Arctic Marine Oil Spill Program no: 13 (AMOP, Environment Canada, Canada, pp. 119-138, 1990.

Daling, P.S., Leirvik, F., Reed, M., Almås, I.K., Brandvik, P.J., Hansen, B.H., Lewis, A., Reed, M., 2014. Surface weathering and dispersibility of Macondo MC252 crude oil. Mar. Pollut. Bull. 87 (1–2), 300–310.

EMSA 2016: European Maritime Safety Agency dispersant inventory: http://www.emsa.europa.eu/opr-documents/opr-inventories.htm.

Equinor 2017: Open oil spill contingency analysis for Johan Castberg (in Norwegian): https://www.equinor.com/content/dam/statoil/documents/impact-assessment/johan-castberg/statoil-pl532-johan-castberg-ku-oppsummering-av-h%C3%B8ringsuttalelser-og-tilsvar-vedlegg-4-beredskapsanalyse-av-oljevern.pdf.

Equinor 2018: Open oil spill contingency analysis for Gjøkåsen (In Norwegian): http://tema.miljodirektoratet.no/Documents/Skjema/Beredskapsanalyse%20Gjøkasen.PDF

Faksness, L.G., P.J. Brandvik, P.S. Daling, I. Singsaas, S.E. Sørstrøm. 2016: The value of offshore field experiments in oil spill knowledge and technology development for Norwegian waters. Marine Pollution Bulletin 111. Pp. 402-410.

French-McCay, D., Deborah Crowley, Jill J. Rowe, Michael Bock, Hilary Robinson, Richard Wenning, Ann Hayward Walker, John Joeckel, Tim J. Nedwed, Thomas F. Parkerton. 2018: Comparative Risk Assessment of spill response options for a deepwater oil well blowout: Part 1. Oil spill modeling, Mar. Poll. Bull.,Vol. 133, 2018.

Johansen, Ø., 2000. DeepBlow – a Lagrangian Plume Model for Deep Water Blowouts. Spill Sci. Technol. Bull. 6, 103–111. doi:10.1016/S1353-2561(00)00042-6.

Johansen, Ø., Rye, H., Cooper, C., 2003. DeepSpill—Field Study of a Simulated Oil and Gas Blowout in Deep Water. Spill Sci. Technol. Bull. 8, 433–443. doi:10.1016/S1353-2561(02)00123-8.

Johansen, O., Brandvik, P.J., Farooq, U., 2013. Droplet breakup in subsea oil releases - Part 2: Predictions of droplet size distributions with and without injection of chemical dispersants. Mar. Pollut. Bull. 73, 327–335. doi:10.1016/j.marpolbul.2013.04.012

Jørgensen, K. 2017: NOFO – Development of a common strategy for Operating companies and oil spill response organisations. In proc. International Oil spill Conference 2017.

Kristoffersen, I. 2017: NOFO – How we do operative training. In proc. International Oil spill Conference 2017.

NCA 2018: Preventing Acute Pollution: https://www.kystverket.no/globalassets/om-kystverket/brosjyrer/brosjyre_en_lr.pdf)

Leirvik, F., Resby, J.L.M., 2007. New Oseberg blend oil properties and weathering properties related to behavior at sea. SINTEF Report F06331, pp. 90 (Trondheim, Norway (in Norwegian).

Lehr, B., Bristol, S., Possolo, A., 2010. Oil Budget Calculator, Deepwater Horizon, Technical Documentation.

Lunel, T., Davies, L. and Brandvik, P.J., 1995: "Field trials to determine dispersant effectiveness at sea", in Proceedings from Arctic Marine Oil Spill Program no: 18 (AMOP), Environment Canada, Canada, pp. 603-627, 1995.

Makatounis, P.E., Skancke, J., Florou, E., Stamou, A., Brandvik, P.J. 2017: Management of oil spill contamination in the Gulf of Patras caused by an accidental subsea blowout. Mar. Pollut. Bull. Volume 231, (2017), pp. 578-588.

Nedwed, T.J., 2017. Overview of the American Petroleum Institute (API) Joint Industry Task Force Subsea Dispersant Injection Project. In: International Oil Spill Conference Proceedings, vol. 2017(1). pp. 678–703. http://dx.doi.org/10.7901/2169-3358-2017-1-678.

NOFO 2009: Operative procedures and capabilities: https://www.nofo.no/globalassets/pdfs/operativ-organisering/nofo-standard-2009---engelsk-versjon.pdf

NOFO 2019: Specifications of strategies, equipment and capabilities(in Norwegian) : https://www.nofo.no/planverk/forutsetninger/ytelse/effektivitet/

OSRL 2018: Description of services and equipment: https://www.oilspillresponse.com/services/member-response-services/equipment-list/

OSRL 2017: World wise dispersant storage: https://www.oilspillresponse.com/services/member-response-services/dispersant-stockpiles/

Reed, M., Daling, P.S., Brakstad, O.G., Singsaas, I., Faksness, L.-G., Hetland, B., Ekrol, N., 2000. OSCAR2000: a multi-component 3-dimensional Oil Spill Contingency and Response model, in: Arctic and marine oilspill program technical seminar. Environment Canada; 1999, pp. 663–680.

Slagstad, D. & Mcclimans, Thomas. (2005). Modeling the ecosystem dynamics of the Barents Sea including the marginal ice zone: I. Physical and chemical oceanography. Journal of Marine Systems. 58. 1-18. 10.1016/j.jmarsys.2005.05.005.

Wassmann, P., Slagstad, D., Riser, C.RE., and Reigstad, M. 2006: Modelling the ecosystem dynamics of the Barents Sea including the marginal ice zone: II. Carbon flux and interannual variability, Journal of Marine Systems,Volume 59, Issues 1–2, 2006.