Polluting shipwrecks in Swedish waters: investigations, risk assessment methodology and oil removal operations

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ABSTRACT

Large amounts of oil exists in old shipwrecks worldwide, both as cargo and bunker. This oil will eventually enter the marine environment as the ship hulls deteriorate or as other types of activities affect the wrecks. Oil being a complex mixture of hazardous substances will when released into the marine environment be a source of both lethal and sub-lethal effects to organisms. Costs of an oil spill in the marine environment, including clean-up actions, socioeconomic and environmental costs is often substantial. Sweden has a ten year nationally funded program where oil removal operations on shipwrecks are performed. From a list of 300 potentially polluting shipwrecks, 31 wrecks have initially been selected for oil removal operations. In a first stage extensive gathering of information was performed regarding each wreck, both archive data and in-situ data at the wreck site. Secondly, a risk analysis was carried out. Based on the probability of oil leakage, amount of oil in the wreck and sensitivity of recipients, a prioritization for oil removal operations was made of the 31 wrecks. Based on the prioritization, time of the year and cost of an operation wrecks are finally selected for oil removal operation. So far, since 2017, five operations have been performed.

During 2019 and 2020, two successful oil removal operations were carried out. The ship Lindesnäs wrecked 1957 in a snow storm close to the lighthouse Norra Kränkan on the Swedish east coast with a cargo of kerosene and diesel as bunker fuel. The operation from mobilization to demobilization lasted for 22 days, and 299 m^3 of oil and a large ghost net was removed from

the wreck. Secondly, Finnbirch, which wrecked in 2006 east of the island of Öland and started to leak oil during the end of 2018, was salvaged in a two-part operation. In 2019, 60 m^3 of diesel fuel and lubricant oil were salvaged, during a fourteen-day operation. In 2020, 114 m^3 of heavy fuel oil (HFO) was salvaged from the wreck during a fifteen-day operation. The costs per ton of removed oil were far less than cost for oil clean-up operations in Swedish waters. In conclusion, using a risk-based approach for prioritization of potentially polluting shipwrecks and the subsequent proactive removal of oil from shipwrecks is a cost-effective approach to alleviate the problem.

INTRODUCTION

Sources of input of oil into the marine environment are diverse, for example, oil extraction processes, shipping activities, land based sources and shipwrecks (Andersson et al., 2016, Farrington & McDowell, 2004). The total number of shipwrecks in the marine environment worldwide has been estimated to 8600 (>400 GT), where 1600 of these are tankers. In total it is estimated that these wrecks contain somewhere between 2.5 – 20.4 million tons of various oil products (Michel et al., 2005). Sources to shipwrecks are for example accidents, including collisions and groundings, but the major source is ships sunk during wartime, e.g. World War II. Due to deterioration of the ship hull over time, or activities e.g. bottom trawling, construction work or storms or extreme weather the shipwrecks will start to discharge their oil content affecting the marine environment. This process and rate before discharge will depend on factors such as salinity, biological fouling on the hull, construction of the ship, damage during wreckage, sea-floor currents and intensity of the activities mentioned above (Landqvist et al., 2017). Type of discharge can then be chronic discharges, episodic or the one-time release of the total content in the wreck.

Oil can affect the marine environment in different ways, depending on the type of oil, volume spilled, resilience of affected habitats, weather and season at the time of spill and availability of oil degrading microorganisms. Large, one time spills can have acute toxic effects on organisms, hinder oxygen and UV-light transfer into the water column and disable the protection granted by the feathering and fur on such animals against low temperatures and limit their buoyancy in water (Rogowska and Namiesnik, 2010). In contrast, small but continuous oil spills commonly have sub-lethal effects in organisms, caused by the most toxic components in oil, Polycyclic Aromatic Hydrocarbons (PAHs). Consequences in organisms can then be carcinogenic effects, lowered growth and fecundity and lowered taxonomical, genetic and ecological diversity (Lindgren et al., 2017, Rawson et al., 2010). Both types of spills can originate from shipwrecks, through large holes in the hull created by for example a trawl board resulting in a release of the total content of oil or a continuous minor discharge through a small hole due to for example pit corrosion in the hull.

Costs related to oil contamination of the marine environment is often substantial. Clean-up actions are more costly if the oil spill affects shore or near-shore areas, up to four to five times compared to offshore clean-up costs (Etkin 1999, 2000). Socioeconomic costs related to loss of income for fisheries, aquaculture or tourism sector can also be substantial e.g. losses for fisheries, aquaculture and tourism after the *Prestige* oil spill in north western Spain 2002 resulted in losses of €113, €13 and €110 (US $126, $14, $122) million respectively. Finally, environmental costs, the temporal degradation of ecosystem services are often more difficult to estimate in monetary terms. In general only three resources are considered when evaluating costs to the environment, birds, seals and beaches. Other negative effects of oil contamination e.g. lowered fecundity and growth, offspring survival and biogeochemical nutrient recycling by microorganisms are generally not considered (Liu & Wirtz, 2006) and have most likely in the end large economic consequences. In summary, the costs of an oil spill in the marine environment, including clean-up actions, socioeconomic and environmental costs is many times substantial. Therefore, a proactive removal of oil from shipwrecks can be a cost-effective approach to alleviate the problem with oil discharges from wrecks (NOAA, 2013). Rather than taking a reactive approach and remediating areas after a discharge, dealing with clean-up costs and costs associated with socioeconomic and environmental effects described above. In addition, a large proportion of the shipwrecks are older (40-80 years) and often no owner is available that can be claimed of liability for the spill or no environmental laws considering polluter pays principle was enforced at the time of wreckage that can be applied. Therefore, the state in which waters the wreck resides or is affected by the spill will carry the costs of the oil spill. This situation is nowadays resolved for states that has ratified the IMO Nairobi International Convention on the Removal of Wrecks, but the convention cannot be applied on ships that wrecked prior to the states ratification of the convention (IMO, 2007).

In Sweden the problem with polluting shipwrecks has been recognized during several reports from governmental authorities and from research projects, highlighting the costs of oil spill and potential benefits of a proactive approach to the problem. The result being that Sweden now has a ten year nationally funded program where oil removal operations on shipwrecks are carried out. The purpose of this paper is to present Sweden’s national program for polluting shipwrecks, the prioritization of wrecks and two case studies describing the process from risk assessment to oil removal operation. A secondary purpose was to compare the costs for the described oil removal operations to costs for clean-up operations of oil.

METHODS

Background

Initial reports from Lindström (2006) and Hassellöv (2007) concerning the environmental risks with polluting shipwrecks in Swedish waters and costs of oil removal operations of wrecks led to that the Swedish Maritime Administration was issued a governmental remit. This was carried out during 2009-2015 together with the Swedish Agency for Marine and Water Management (SwAM), Swedish Coast Guard, Swedish National Maritime Museums, and Chalmers University of Technology. The objective of the remit was to perform an inventory of shipwrecks in Swedish waters and then narrowing it down to a list of potentially polluting wrecks. From a list of about 17000 objects, including everything from modern wrecks of steel to pieces of planks from centuries old wooden boats, the list was narrowed down to 2700 wrecks using age, position, function and type of ship. In a second step the list was narrowed down to 316 wrecks that could be classified as hazardous to the environment using foremost information regarding the type of fuel for propulsion (coal vs oil). In a final stage a list of 31 shipwrecks was produced, after additional gathering of information concerning the probability of oil still being contained in the wreck. These were classified as an acute environmental threat (SMA, 2011).

During the same time-period, Chalmers University of Technology had a research project addressing polluting shipwrecks. In the project ecotoxicological studies were performed to assess the impacts of small, but continuous oil spills, and a risk analysis method of potentially polluting shipwrecks was developed. The project resulted in new knowledge of effects of low concentrations of PAHs in the marine environment and a risk assessment method for shipwrecks called VRAKA (Landquist 2016, Lindgren 2015). VRAKA is a model that use Bayesian updating for risk assessment of shipwrecks and also includes uncertainties. It consist of two parts: (I) an estimation of the probability of discharge of hazardous substances, and (II) approaches for consequence assessment of a discharge. In the end a user of the tool can compare risk levels associated with different wrecks, in three tiers. Risk estimation in tier 1 is based on:

$$Risk_{total} = P_{Opening} \text{ x } P_{Hazardous\ substance\ contained} \text{ x } V_{Oil},$$

where $P_{Opening}$ is the probability of an opening in the wreck, $P_{Hazardous\ substance\ contained}$ the probability that there is oil still inside the wreck and V_{Oil} is the estimated volume of oil inside the wreck. In the risk assessment process several input data parameters are needed to complete the assessment, for example in situ parameters related to corrosion rates and activities that can affect the wreck e.g. trawling, shipping and storms (Landquist et al., 2017). For more detailed information regarding VRAKA see Landquist et al., 2017.

The results from the governmental remit and university projects gave interest at the governmental level, with the result that a national authority, the Swedish Agency for Marine and Water Management, was given the responsibility for coordinating risk assessment, investigations and recovery operations of oil from shipwrecks in Swedish waters. The project, that runs over 10 years, has an annual funding of approximately $2.4 million (for 2019 $4.22 million and 2020 $2.91 million).

Risk assessment

As a starting point the 31 wrecks reported in the governmental remit were used, since they were reported as an acute environmental threat (Fig. 1). The wrecks are located at all sides of the coast of Sweden, in water depths between 20- 140 m, salinity ranges from approximately 6- 32 Practical Salinity Units (PSU), and human activities that affect the wrecks differ widely in intensity. In a first stage the wrecks were risk assessed using the tier 1 of VRAKA; estimating the probability of a leakage times the volume of oil in the wreck. That resulted in an initial prioritization list for oil removal operations. In a second stage, corresponding to tier 3 in the VRAKA risk assessment (the tier 2 approach, which combines probability of leakage with amount of oil and distance to the shoreline was not used), oil spill trajectory modelling together with sensitivity of receptors of an oil spill were performed. The Swedish Metrological and Hydrological Institute (SMHI) provides a tool for oil spill trajectory modelling, SeaTrackWeb (Ljungman & Mattsson, 2011). This is used for example by the Swedish Coast Guard when an oil spill is detected and predictions are made for where oil remediation actions are needed. However, these predictions are valid four days in the future and six days back from present time. Therefore, in addition to the usage of SeaTrackWeb the SMHI also performed oil spill trajectory modelling from the wrecks over all seasons. Starting points for the simulated oil leakage was varied from six different years (PADM model data from 2005-2011), with the horizontal resolution of two nautical miles. In total 432 oil spill simulations were performed for each wreck and each simulation lasted for 10 days (Höglund, 2019).

Sensitivity of receptors was assessed using the tool Digital Environmental Atlas. In the tool the Swedish coastline is mapped according to physical characteristics. It takes ecological aspects into account, but is mainly based on the difficulty of remediating a specific type of shore. However, areas with high ecological aspects, e.g. Nature 2000 areas gives higher rating in the tool. Altogether, a coastal area can have a rating between 1-18 where high numbers should be prioritized in case of an oil spill accident (Henriksson et al., 2018). In addition, in the tier 3 risk assessment the project used the tool Protected Areas (https://skyddadnatur.naturvardsverket.se/), a GIS based tool hosted by the Swedish EPA that allows a user to easily visualize various forms of protected areas e.g. Nature 2000[1] and marine national parks, on a map over the area where the shipwreck being risk assessed is located.

Based on the results from the risk assessment and the subsequent prioritization shipwrecks are selected for oil removal operations. Provided that there are no legal barriers that hinders an operation, e.g. liability of an owner to perform the operation and that enough funding is available for the project a call-off from SwAMs framework agreement with contractors is completed.

RESULTS/DISCUSSION

Due to confidentiality, the prioritization list of the 31 wrecks is not listed. In total five oil removal operations have been carried out since SwAM, in 2016 was given the responsibility for coordinating risk assessment, investigations and recovery operations of oil

[1] https://ec.europa.eu/environment/nature/natura2000/index_en.htm

from shipwrecks in Swedish waters. Two case studies are presented here, of the wrecks Lindesnäs and Finnbirch, providing information regarding the workflow from risk assessment to oil removal operation.

Lindesnäs

Background

The ship Lindesnäs was built in 1949 at Lindholmen shipyard in Gothenburg, Sweden. It was delivered in 1950 to the shipping company Nordstjernan in Stockholm. The vessel weighed 1,265 gross tonnes and was just over 67 metres long. On April 17, 1957, Lindesnäs was sailing between Nynäshamn and Norrköping, on the east coast of Sweden. It was loaded with 1732 cubic metres of kerosene and unknown amounts of diesel for propulsion. There was a snowstorm and the lighthouse Norra Kränkan had been snowed over, with the consequence that the light displayed the wrong colour. Lindesnäs then passed on the wrong side of the lighthouse and ran aground. All 20 crew members was rescued to safety in the lifeboats. Later on the ship drifted off the ground and sank in deeper waters. The wreck has today been lying for 63 years on the sea floor. It is positioned on its port side at a depth of about 70 metres in an area where the sea-floor sediment consists of compact clay. The wreck is located about 10 kilometres off the coast of the town Oxelösund (Fig. 1). During an in-situ investigation in early 2019 using photogrammetry the wreck was shown overall be in good condition and oil was expected to still be present (Fig. 2.).

Risk assessment

The wreck was selected for oil removal operation as the risk assessment using VRAKA placed it at second place in the prioritization of the 31 wrecks. This was mainly due to the factors deterioration, military activity in the area and the possible large amounts of oil in the wreck. One wreck has a higher risk level, but it is not possible to perform an oil removal operation today due to lack of funding. Oil spill trajectory modelling using the SeaTrackWeb tool and modelling over the seasons (se methods) showed that an uncontrolled discharge of oil from the wreck will likely end up southwest of the wreck´s position, affecting two Nature 2000 areas – Bråviken and Hävringe-Källskären (Fig. 3). Areas that are listed as prioritized in Digital Environmental Atlas. Bråviken is a marine nature reserve, which includes hundreds of islands and islets. It has a rich plant and animal life, both on land and in water. The area is also known for its outdoor activities and recreational fishing. Hävringe-Källskären is one of the most important areas for grey seals (*Halichoerus grypus*) in the Baltic Sea. It is also an important area for the Caspian tern (*Hydroprogne caspia*), as large numbers breed on the islands.

Oil removal operation

A detailed investigation and oil removal operation of Lindesnäs was carried out during August and September 2019. SwAM led the work, where the dive operation was implemented by a Danish contractor. Inspection holes were drilled in cargo tanks, bunker tanks, engine room, pump room and lubricant oil tanks. Oil was detected in four cargo tanks, in the engine room and in a pump room. On the topmost part of the tanks where oil was detected a flange was attached, a hole drilled and hot-tapping equipment attached. Thereafter, work began on emptying the tanks by pumping the oil (consisting of kerosene or diesel) to work vessels on the surface. As kerosene has a low flash point and therefore strict regulations for handling and storage is was pumped directly to a product tanker. The salvaged oil was then transported to shore for recycling in an oil refinery and the amount that could not be recovered was sent for incineration. In total, 299 cubic metres (~1880 barrels) of oil was removed from different compartments in the wreck. During the operation, the hull was penetrated in a controlled environment to avoid oil leakage. The drilling and subsequent pumping of oil was carried out with a closed system and a pyramid shaped dome was lowered above the area where work was conducted, collecting any oil that might anyhow escape from the wreck. In addition, during the oil removal operation, a 46 meter long ghost net (lost fishing gear) was found attached to the wreck, with two dead seals trapped in it. The ghost net was recovered and transported to shore for recycling and destruction. The oil removal operation and recovery of the ghost net amounted to a total cost of approx. $1.94 million.

Finnbirch

Background

The ro-ro ship Finnbirch was built 1978 in the Hyundai Heavy Industries shipyard in South Korea. The vessel was 156 m long and 22.7 m wide, with a gross tonnage of 15396 tons. During a voyage in October 2006 with very rough weather between Helsinki, Finland and Århus, Denmark with a cargo of trailers and large, heavy bales of paper there was a load shift due to bad cargo management. The ship suffered from heavy listing and sank a couple of hours later. The ship is today located on a depth of 82 m, east of the island of Öland on the Swedish east coast. The ship had about 441 m^3 of bunker fuel - heavy fuel oil (HFO), 100 m^3 of diesel fuel and approximately 10 m^3 of lube oil on-board. Some 200 m^3 of HFO was estimated to have leaked during the wreckage. During 2007 the insurance company for the ship hired a salvage company to perform an oil removal operation where in total 150 m^3 of HFO and diesel were salvaged. However, the salvage company was unable to get access and recover oil from a fuel tank between the two propeller tunnels, containing some 85 m^3 of diesel fuel.

Risk assessment

Finnbirch was initially not selected for oil removal operation during 2019 as it was ranked as no 13 in the tier 1 risk assessment with VRAKA. Being at the seafloor only for 12 years it has not yet been affected by corrosion in any high degree. However, in the turn of the year between 2018 and 2019 the Swedish Coast Guard reported oil leakage from the wreck. After commendable work by the Coast Guard a box like construction was placed over the leak, a hose attached and connected to a buoy at the surface. The hose could then be used to empty the oil that had gathered in the box. However, this task tied up Coast Guard resources, needed elsewhere. With an active leakage Finnbirch was upgraded to place number three in the tier 1 risk assessment. Furthermore, the oil spill trajectory scenarios showed that an oil leakage from the wreck could affect the east coast of the island of Öland with the Nature 2000 areas Egby sjömarker and Kapelludden. At both areas there are established wet meadows and connecting shallow coastal areas acting as important spawning and nursery grounds for fish. The southern parts of the island of Gotland and south and southeast of the wreck could also be affected by a spill. These areas hosts several large Nature 2000 area called Hoburgs bank and Midsjöbankarna which consists of large spawning and winter grounds for the Long-tailed duck (*Clangula hyemalis*) and important calving and spawning areas for harbour porpoises (*Phocoena phocoena*) (Carlström & Carlén, 2016, Larsson & Tydén, 2005) (Fig. 4).

Oil removal operation

After a lengthy juridical inquiry by the Swedish EPA, an oil removal operation could be initiated. There still exists an owner to the wreck that could be claimed for liability, however, the ship-owner had a limit of liability fund where the limit had been reached, and hence no claim could be put on the owner to remove the oil.

SwAM led the work, and the dive operation was carried out by a Danish contractor from the frame work agreement. Inspection holes were drilled in the tank between the propeller tunnels. However, no oil remained in the specified tank. A decision was then taken to inspect tanks that was according to reports emptied of oil during the salvage operation in 2007, and also other areas. In total 14 additional areas were inspected. Oil was found in six areas; starboard store room, hydraulic room, auxiliary engine room, in two port side double bottom fuel oil tanks and in a water ballast tank. As by default, a flange was attached on the topmost part of the tanks where oil was detected, a hole drilled and hot-tapping equipment attached. Thereafter, the tanks were emptied by pumping the oil (marine diesel) to the work vessel on the surface. Besides diesel, heavy fuel oil (HFO) was also detected in the two double bottom fuel oil tanks. This should have been recovered during the initial operation in 2007, therefore, this was not stated in the contract and the contractor had no equipment for heating and recovering HFO. Therefore, a second part of the operation was performed in august 2020, with equipment for heating and pumping HFO. Flanges were attached to the topmost parts of the two port side double bottom fuel oil tanks, holes drilled and hot-tapping equipment with built-in Archimedes DOP 40 pump attached. Holes for steam injection and heating HFO were drilled just below the flanges. As much oil as possible was first pumped to the work vessel using only the Archimedes pump, until the oil and water interphase was reached. Then steam injection using steel pipes commenced and lasted for about 24h. After the process additional HFO could be salvaged. In total 173.7 m^3 (~1093 barrels) of oil (60 m^3 of diesel and 113.7 m^3 HFO) were removed from the shipwreck to a cost of approx. $2.55 million. As in the operation with Lindesnäs, the hull was penetrated in a controlled environment to avoid oil leakage. The drilling and subsequent pumping of oil was carried out with a closed system and a pyramid shaped dome was lowered above the area where work was conducted, collecting any oil that might anyhow escape from the wreck.

Cost Comparison -- Overall

Oil spill clean-up at sea and on the coastline after a spill is very costly, even without including cost of loss of tourism and aquaculture or damage to the environment. Equipment, vessels and personnel costs are examples of direct clean-up costs (Andersson et al., 2016). An oil spill in areas with high environmental values or major tourism activity would highly increase the costs of the spill. An example of costs of an oil spill affecting the Swedish coastline, is the so-called Tjörn spill in 2011. In September 2011 a collision in Skagerrak between the cargo ship Golden trader (192 x 32 x 15.7 m) and a fishing vessel led to an oil spill of bunker fuel. The oil was transported by currents to west coast of Sweden and affected the archipelago of the municipality of Tjörn. An intense clean-up operation, both on sea and shoreline, over several months recovered some 500 tons of oil at costs of $16.25 million (MSIR, 2012). An international example is the Prestige oil spill in 2002 outside the north-western coast of Spain were 60 000 tons of crude oil were spilled and the clean-up costs amounted to $560 million (Loureiro, 2006). Of course clean-up costs depends on several factors, such as type of oil, characteristics of the spill location, weather and sea conditions, amount spilled, time of the year and effectiveness of clean-up (Etkin, 1999, 2000, White & Molloy, 2003). Hence, costs will differ between spills and in general clean-up at sea is less costly than clean-up at the shore.

In addition to direct clean-up costs there are socioeconomic and environmental costs. Aquaculture, fisheries and tourism are the main industries connected to socioeconomic costs. Harvested fish and other seafood might become inedible or not allowed to sale due to restrictions. Oiled beaches results in economic losses for stakeholders in the tourism sector, as the number of tourist's decreases. In the case for the Prestige accident socioeconomic costs was estimated to $135 million (Loureiro, 2006). Finally, environmental costs of an oil spill results in temporal degradation of natural resources and services. Assessment of costs in this area is mainly focused on beaches, birds and seals. Not taking into account other habitats or other effects in animals besides lethal consequences, e.g. productivity, fecundity or decreased ecosystem services (Andersson et al., 2016, Lindgren et al., 2012, Liu et al., 2006). Altogether, costs of oil spills, including all types of costs, are very high. Comparing costs for oil removal from the wrecks Lindesnäs and Finnbirch, $7476/ton and $17542/ton (weigh of marine diesel 1150 litres/ton, HFO 1008 litres/ton) respectively, to only the direct clean-up costs for the oil spill at Tjörn and the Prestige, $47000/ton and $14900/ton, in 2020 monetary terms you realize that there is most probably a cost benefit in applying oil removal operations from shipwrecks proactively. Furthermore, Etkin (1999) compared oil spill clean-up costs at different continents. Using these numbers, including inflation, in 2020 monetary terms results in clean-up costs in United States at $38142/ton (excluding Exxon Valdez), Canada $99958/ton, Europe $13924/ton and Asia $24310/ton. However, the costs for clean-up have increased at a higher rate compared to inflation. Firstly, there is now a greater expectation from public and government authorities on the thoroughness of the clean-up. The clean-up operations have then become more thorough and complex, and therefore costly. Secondly, there is now a larger dataset of clean-up operations to base the estimations on, compared with 1999. Clean-up costs for a spill in Europe, offshore, of light oil (as in the case study shipwrecks Lindesnäs and Finnbirch part 1) 2020 ranges between $495000 – 49500/ton and for heavy oil (as in the case study shipwreck Finnbirch part 2) it 2020 ranges between $1050000 – 105000/ton, depending of the volume of the spill (pers. comm. D. Etkin, 2019). Hence, clean-up costs of oil is in most cases larger comparing to proactively removing oil from a shipwreck. Of course, costs also depends of the state's ability or willingness to perform clean-up operations. The costs are then instead displaced to socioeconomically and environmental costs. This is based on the two case studies presented here. However, taking into account other successful oil removal operations where external contractors performed the work, the costs is comparable, average cost $26598/ton (st. dev. ±$21297, updated to 2020 monetary terms), to the operations presented here (NOAA, 2013).

One could argue that there is an uncertainty in the complete removal of all oil from the shipwreck, and the input of oil into the marine environment cannot completely be avoided. Or that the shipwreck has, on the contrary to the information at hand, no or nearly no oil on board when an oil removal operation is carried out. With the consequence of very high cost per removed ton of oil, e.g. Solar I and Palo Alto with costs of $1737000/ton and $1370000/ton (updated to 2020 monetary terms) of oil respectively (NOAA, 2013). However, in oil spill clean-up operations, the total amount of the oil spill is rarely recovered, with large volumes of oil affecting the environment. For example from the Exxon Valdez spill only 14% of the oil was recovered (McNutt, 2014, Wolf et al., 1994).

If also socioeconomic and environmental costs is included in the cost-benefit estimate, it will strongly indicate that acting proactively instead of reactively to oil spills is beneficial. Tourism is many times a multimillion industry in coastal and near-coastal areas. The industry is then negatively affected by an oil spill as tourists reject contaminated areas. This is also accurate for Sweden and the Swedish coastline, which is one of the longest in Europe. The value of tourism in Sweden 2018 was $33 billion (SAERG, 2018).

Besides economic costs, there is further benefits of a proactive approach, in removing the threat of oil entering the marine ecosystem. The environmental stress on the ecosystem is avoided, as the subsequent effects on marine biota. Marine ecosystems is today often exposed to large number of various anthropogenic stressors e.g. eutrophication, hazardous substances, climate change, that affects marine organisms in additive or even synergistic manner. This is especially true for the sensitive and heavily stressed Baltic Sea (HELCOM, 2018), in which most of the Swedish oil containing shipwrecks is located. By removing oil from shipwrecks, one potential anthropogenic stressor is avoided.

CONCLUSIONS

Here we present the Swedish national program addressing the problem with polluting shipwrecks; the inventory, risk assessment and case studies. This risk-based approach and prioritization of oil removal operations is applied to minimize the risk of oil entering the marine environment. During 2019 and 2020, two operations were performed, with the result of 473 m^3

(2975 barrels) of oil were prevented from eventually entering the marine environment. By proactively removing oil from shipwrecks, the anthropogenic stress caused by the oil spill is avoided. The cost of oil removal operations are substantial, however, oil spill clean-up operations, socioeconomic and environmental cost are, when summed, higher. Moreover, you could argue that there is a moral obligation of ameliorate or remove threats to the marine environment caused by man.

REFERENCES

Andersson, K., Brynolf, S., Lindgren, J.F., Wilewska-Bien, M. 2016. Shipping and the Environment – Improving environmental performance in marine transportation. Springer-Verlag. Heidelberg.

Carlström, J., Carlén, I. 2016. Skyddsvärda områden för tumlare i svenska vatten [Important areas for harbour porpoises in Swedish waters]. AquaBiota Report 2016:02.

Etkin, D. S., 1999. Estimating cleanup costs for oil spills, in International Oil Spill Conference. 1999.

Etkin, D. S., 2000. Worldwide analysis of marine oil spill clean-up cost factors, in Proc 23rd Artic and marine oil spill program technical seminar.

Farrington, J. F., McDowell, J. E., 2004. Mixing and Water. Oceanus. 43(1): p. 46-49.

Hassellöv, I. M., 2007. Förstudie om vraksanering [Prestudy on the remediation of shipwrecks]. Göteborg, Sweden: Alliance for Global Sustainability (AGS).

HELCOM. 2018. State of the Baltic Sea, second HELCOM holistic assessment 2011-2016. Baltic Sea Environment Proceedings 155.

Henriksson, J., Stadmark, J., Hellsten, S. 2018. Nationellt prioriteringsskikt i Digital Miljöatlas. MSB1306.

Höglund, A,. 2019. Oljespidning från vrak (Oil spill trajectories from shipwrecks). SMHI.

IMO. 2007. Nairobi International Convention on the Removal of Wrecks.

Landquist, H. 2016. Environmental risk assessment of shipwrecks – Model development and application. Chalmers University of Technology.

Landquist, H., Rosén, L., Lindhe, A., Hassellöv, I.-M., 2016. VRAKA—a probabilistic risk assessment method for potentially polluting shipwrecks. Front. Environ. Sci. 4.

Landquist, H., Rosén, L., Lindhe, A., Norberg, T., Hassellöv, I.-M. 2017. Bayesian updating in a fault tree model for shipwreck risk assessment. Science of the total environment, 591:80-91.

Larsson, K., Tydén, L. 2005. Effects of oil spills on wintering Long-tailed ducks *Clangula hyemalis* at Hoburgs bank in central Baltic Sea between 1996/97 and 2003/04. Ornis Svecica 15: 161-171.

Lindgren, J.F. 2015. Evaluating effects of low concentrations of oil in marine benthic communities. Chalmers University of Technology.

Lindgren, J.F., Hassellöv, I-M., Dahllöf, I. 2012. Meiofaunal and bacterial community response to diesel additions in a microcosm study. Marine Pollution Bulletin, 64: 595-601.

Lindgren J.F., Hassellöv, I-M, Rattfelt Nyholm, J., Östin, A., Dahllöf, I. 2017. Induced tolerance in situ to chronically PAH exposed ammonium oxidizers. Marine Pollution Bulletin, 120: 333-339.

Lindström, P. 2006. Vrak i Skagerrak- sammanfattning av kunskaperna kring miljöriskerna med läckande vrak i Skagerrak. (Shipwrecks in Skagerrak – a summary of the knowledge regarding leaking wrecks in Skagerrak). County administrative board of Västa Götaland.

Liu, X., Wirtz, K. W. 2006. Total oil spill costs and compensations. Maritime Policy & Management, 33(1): p. 49-60.

Ljungman, O., Mattsson, J. 2011. Scientifc Documentation of Seatrack Web;
physical processes, algorithms and references. The Swedish Meteorological and Hydrological Institute. http://www.smhi.se/professionella-tjanster/professionella-tjanster/sakerhet-och-beredskap/seatrack-web-spridningsprognoser-for-oljeutslapp-och-andra-fororeningar-1.1646 (Accessed 21 Novermber,2019.

Loureiro, M. L., Ribas, A., Lopez, E., Ojea, E. 2006. Estimated costs and admissible claims linked to the Prestige oil spill. Economical Economics, 59: 48-63.

Marine Safety Investigation Report. 2012. Marine safety investigation report – Joint safety investigation into the collision between the Maltese bulk carrier Golden Trader and the Belgian fishing vessel Vidar. 2012: 18.

McNutt, M. 2014. Exxon Valdez: 25 years later. Science. 343.

Michel, J., Gilbert, T., Schmidt Etkin, D., Urban, R., Waldron, R., Blocksidge, C.T. 2005. Potentially polluting wrecks in marine waters. International Oil Spill Conference, 1: 1-40.

NOAA. 2013. Risk assessment for Potentially Polluting Wrecks in U.S. Waters.

Rawson, C.A., Lim, R.P., Tremblay, L.A., Warne, M.S., Ying, G.G., Laginestra, E., Chapman, J.C., 2010. Benthic macroinvertebrate assemblages in remediated wetlands around Sydney, Australia. Ecotoxicology, 19: 1589- 1600.

Rogowska, J., Namiesnik, J., 2010. Environmental Implications of Oil Spills from Shipping Accidents. In: Reviews of Environmental Contamination and Toxicology, Springer, New York. 206: 95-114.

SMA. 2011. Miljörisker från fartygsvrak [Environmental risks from shipwrecks]. Swedish Maritime Administration. Governmental remit 2009/4683/TR.

Swedish Agency for Economic and Regional Growth (Tillväxtverket). 2018. Fakta om svensk turism 2018 (Facts regarding Swedish tourism 2018.

White, I.C., Molloy, F.C. 2003. Factors that determine the cost of oil spills. IOSC 2003.

Wolfe, D. A., Hamaeedi, M. J., Galt, J.A., Watabayashi, G., Short, J., O´Claire, C., Rice, S., Michel, J., Payne, J., Braddock, J., Hanna, S., Sale, D. 1994. The fate of the oil spilled from the Exxon Valdez. Environmental Science and Technology, 28: 560-568.

FIGURES

Figure 1. The 31 shipwrecks that is included in the national program.

Figure 2. In-situ image of the shipwreck Lindesnäs produced using photogrammetry.

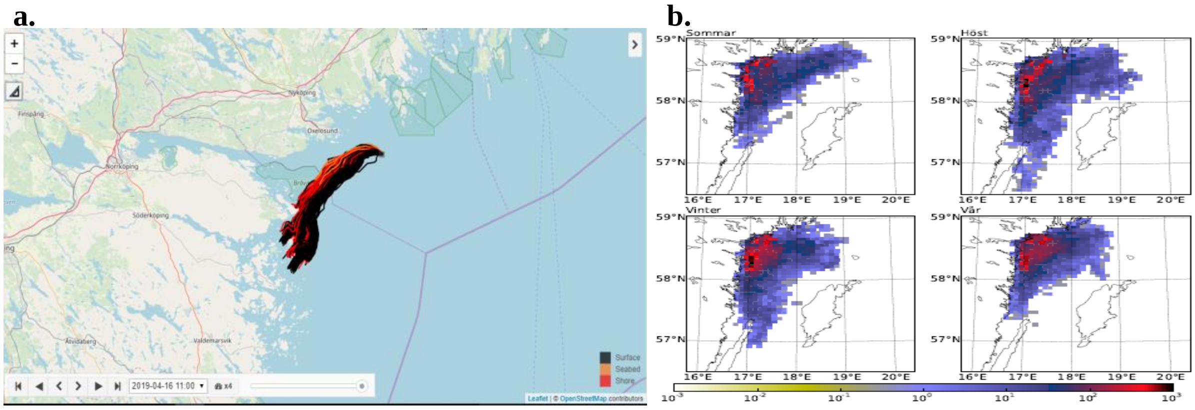

Figure 3. a. Oil spill trajectory modelling of a spill from the wreck Lindesnäs using SeaTrackWeb and b. over the four seasons. Top left is summer, top right autumn, lower left winter and lower right spring. The scale represent amount of oil after 10 days simulation per km².

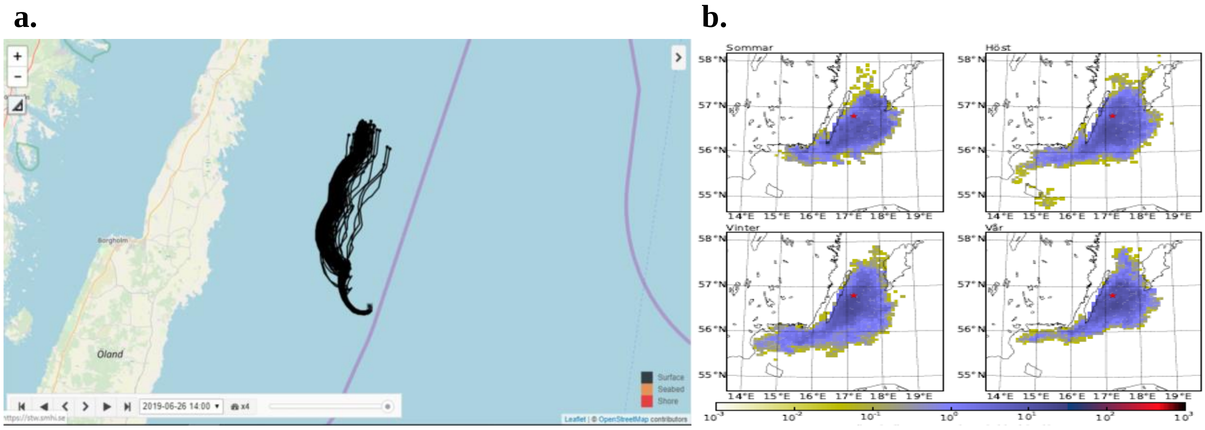

Figure 4. a. Oil spill trajectory modelling of a spill from Finnbirch using SeaTrackWeb and b. over the four seasons. Top left is summer, top right autumn, lower left winter and lower right spring. The scale represent amount of oil after 10 days simulation per km².