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GENERAL METHODOLOGY OF OIL REMOVAL OPERATIONS ON BALTIC SHIPWRECKS

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GENERAL METHODOLOGY
OF OIL REMOVAL OPERATIONS ON BALTIC SHIPWRECKS

Proposition of a wreck management programme for Poland

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CHAPTER 1: INTRODUCTION

There are many factors that can negatively affect the marine environment. The shipwrecks located on the seabed are one of them and can contaminate both the water and the seabed with various types of ship fuels and other hazardous substances, including conventional and chemical weapons. All of which pose a serious threat to the marine ecosystems and the environment. It is a global problem, particularly detrimental in enclosed sea basins, such as the Baltic Sea or the Black Sea. Hostilities during both world wars as well as intensive exploitation of maritime transport routes have resulted in the deposition of thousands of warships and commercial vessels containing large quantities of various fuels on the seabed.

When categorizing potentially dangerous wrecks according to their environmental impact, the following types of wrecks are taken into account: wrecks of ships powered by or transporting: 1) heavy fuels (such as mazut), 2) carbon liquids derived from carbon hydrogenation, 3) diesel fuels or 4) other liquid or semi-liquid hazardous chemical substances. In the Polish EEZ these are mainly the wrecks that sank during the First and Second World War or later.

The term "dangerous wreck" should be used in relation to wrecks that contain in their tanks (or any other enclosed spaces) fuel or/and other chemical substances hazardous to the environment in quantities greater than 10 m3, and are located less than 10 miles away from the coast that is a sand beach, rocky beach or a cliff. Depending on such parameters as: the amount of fuel, the distance from the coast and the type of the coastline, we have introduced a concept of the RISK DEGREE:

- **MODERATELY DANGEROUR or DANGEROUS WRECK – is a shipwreck containing from 10 to 500 m^3 of fuel, lying at a distance of 1 to 10 nautical miles from sandy, cliff, rocky or gravel beaches;**
- **VERY DANGEROUS WRECK – is a shipwreck containing more than 500 m^3 of fuel and lying at a distance less than 1 nautical mile from the coast.**

When classifying shipwrecks, apart from the above formal differentiation, other parameters – such as the uniqueness of the site, where the wreck is located (e.g. closeness of natural reserves, protected areas of unique environmental value), presence of endangered fish and other marine or endemic species, as well as many other environmental aspects – should be taken into account.

It is estimated that worldwide there are around 8 600 shipwrecks (larger than 400 GT) that pose a potential threat to the marine environment. Many of them are the remains from the Second World War and their condition has been deteriorating for over 70 years. It is estimated that these wrecks contain from 2.5 to 20.4 million tonnes of petroleum products. They pose an extremely serious threat to the marine environment and in many parts of the world, in the event of a fuel leak, we may be dealing with local ecological disasters with irreversible consequences for the environment.

In the Baltic Sea region, the greatest number of registered wrecks is located in Swedish waters, where among 30,000 identified underwater objects, a significant part is classified as wrecks or wreck remains from various periods of navigation, including 2,700 wrecks of fuel-powered units with a size above 100 GT. Until now, 316 of those wrecks have been classified as potentially DANGEROUS, including 30 considered as VERY DANGEROUS for the environment. It is estimated that in total these wrecks contain from 1,000 to 15,000 tons of bunker oil.

Finland reports 5,200 shipwrecks, including 420 dangerous wrecks, each containing from a few to more than 100 tonnes of fuel. In Denmark, the shipwreck database contains 2 518 records, without the distinction of the risk posed to the environment, although it should be assumed that there are at least a few dozens of such wrecks. The Polish register indicates the presence of more than 400 shipwrecks, of which at least 18 should be considered as potentially dangerous to the environment. Out of 30 wrecks examined by the Maritime Institute in Gdańsk, at least 4 are dangerous. Other Baltic countries report shipwrecks without determining the magnitude of the environmental risk posed by them.

Regardless of the source of the information, the shipwrecks are recognized as a potential risk to the environment. The problem requires systemic measures taken by the authorities responsible for the protection of marine waters and for prevention of pollution of the coastal areas, in particular the beaches, which are a very sensitive ecosystem.

Awareness of environmental risks and damages caused by oil spills has pushed many countries to undertake institutional measures aimed at studying and cleaning the wrecks. Many countries, among others the United States, have a separate, fixed budget dedicated to this purpose and carry out systemic measures in this field. In the United States, there are three universities and one underwater national park (located near Florida) that deal with this issue. Every year, 2-3 wrecks selected out of 573 identified as dangerous wrecks are cleaned. In the United Kingdom, a department of Salvage and Marine Operations (SALMO) operating under the Ministry of Defence, implements a Wreck Management Programme, which permits to study and clean between 2 to 5 wrecks every year (out of over 500 wrecks considered as potentially dangerous). Norway also carries out a national Wreck Programme and between 1994 and 2013 had cleaned 8 wrecks (out of 350 classified as dangerous, including 30 very dangerous ones). In Sweden, Chalmers University in Goteborg constructed the VRAKA system used by the Swedish Agency for Marine and Water Management for risk management and data collection. As a result of the activities carried out in Sweden, 2-3 wrecks are cleaned annually, out of 316 potentially dangerous ones, including 30 classified as very dangerous ones. In Finland, the Finish Environmental Institute (SYKE) runs an extensive program of wreck research and cleaning. Here as well, 2-3 wrecks per year are cleaned (out of 420 dangerous wrecks, including 46 very dangerous ones). In 2020, the tanks of 3 wrecks were emptied using the *Aranda* research ship and more than 20 tons of fuel have been "sucked" from their tanks.

In Poland, thus far, no wreck management system has been introduced. Between 1999-2016, the Maritime Institute in Gdańsk carried out research on the threats posed by wrecks as part of the Finnish review of wrecks commissioned by HELCOM (The Baltic Marine Environment Protection Commission). However, the project did not lead to cleaning of a single wreck, despite documented risks posed by at least 4 wrecks located in the Polish EEZ. The best, but at the same time the most expensive way to prevent the risk, would be to remove the wrecks before fuel or other dangerous substances start leaking. While this is possible, in the case of new wrecks, it is also a very expensive solution (the cost of cleaning can be compensated by P&I insurance). Unfortunately, wrecks older than 50 years are usually in a very poor condition due to the progressive corrosion and the only cleaning option is to locate the space in the wreck, where fuel or other substances are located (mainly tanks) and mechanically remove the pollutants (e.g. through pumping).

However, when using this method, in the case of some wrecks, there is a risk of uncontrolled outflow of hazardous substances. And as a result of contamination of the seabed, water or sea shores with fuel flowing out of shipwrecks, the problem of liability for the effects of pollution and for costs of the conducted spill removal/remediation actions, arises. In the case of wrecks from the period of World War I and II, as well as the post-war wrecks from the period before the introduction of adequate legal regulations, the liability for damage was borne by the state in whose marine area such an event took place. In the case of Poland, the costs were borne by the Maritime Administration. However, since the following regulations have been introduced: 1) International Regulations for Preventing Collisions at Sea 1972 aka COLREGs, 2) International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) – in particular the provisions relating to special areas, 3) the SOLAS Convention (International Convention for the Safety of Life at Sea) and 4) the Nairobi Convention of 2007 (NWRC) – a new provision, the so called *Polluter Pays Principle*, came into force.

The purpose of this methodology is to analyze the available wreck survey methods aimed at determining the size and type of threats posed by wrecks. Moreover, this report presents a systematic methodology for dealing with wrecks assessed as potentially dangerous. This publication contains a number of important information on: the methods of searching for new and assessing the condition of already known wrecks, their potential negative impact on the marine environment, ways of reacting to situations where a leak has already taken place, methods of fuel removal from the tanks (on the example of the Franken wreck), and remediation of the seabed around the wrecks where the leakage has already occurred (for example the Franken and Stuttgart wrecks).

An effective methodology should be based on the so called good maritime practices. Therefore, there is a need to review the available literature, as well as to analyse the existing and implemented operating methods. Appropriate support in decision-making is needed to prioritise and effectively use the resources necessary to carry out preventative or corrective actions. Risk assessment and the overall risk management are important measures to provide such support to the authorities responsible for taking key decisions. Consequently, the proposed actions are based on the probabilistic models defining the risk management framework and on a comprehensive risk assessment models for potentially polluting shipwrecks. Systemising the existing knowledge and indicating the possibilities of applying the existing tools in risk assessment, enhances the ability to deal with the huge uncertainty related to the potential risks posed by shipwrecks. It also facilitates the prioritisation of measures with regard to potential oil spills from shipwrecks and effective resource allocation if such environmental risks occur.

One of the important tasks of the maritime administration, responsible for fulfilling the governmental objectives concerning water and shore protection against oil spills, is to maintain mobile forces and resources to respond to fuel leakage from ships and wrecks. In Poland, this function is fulfilled by the Maritime Search and Rescue Services (SAR). SAR maintains adequately equipped sea ships and land forces to combat oil spills. SAR does not deal with removing oil from wrecks lying at the sea bottom, but only with removing the effects of spills.

The environmental risk posed by each wreck is unique in terms of the probability of leakage and its potential impact on the marine environment. Each shipwreck will react differently to external forces such as currents, waves (especially during storms) and the impact of large vessels moving in close vicinity. The risk assessment of the shipwreck requires a multisectoral knowledge and co-operation between several authorities in order to take appropriate decisions on mitigation measures. Many governmental, scientific and non-governmental institutions are interested in this problem. These include, in particular: 1) the Maritime Administration, e.g. maritime offices administering, on behalf of the State, the areas along the Polish coast and responsible for the state of the marine environment, 2) the Ministry of Environment responsible for maintaining the proper state of the marine environment, 3) universities and marine institutes (ex. The Gdańsk University, Maritime Academy in Szczecin, Maritime Institute of the Maritime University in Gdynia, Sea Fisheries Institute and others) conducting different scientific projects aimed at determining the quality of the marine environment, including water purity and potential threats (such as wrecks, conventional and chemical weapons, overfishing), and 4) non-governmental organisations, such as the MARE Foundation, conducting environmental and educational projects in the field of marine conservation and supporting government activities aimed at improving the state of the Polish marine waters.

This report provides an overview of the available wreck assessment and management strategies and proposes an individual model suitable for wreck management in Poland. The purpose of this report is to: 1) define the methodology of appropriate proceedings of relevant services and research units when examining newly discovered and well explored wrecks in context of their negative impact on the marine environment; 2) present methods of estimating the risk of oil spills from wrecks and methods of geophysical, geological, chemical and ecotoxicological examination of wrecks; and 3) present available methods and technologies for fuel removal from wrecks and the seabed, as well as remediation methods of contaminated sediments.

CHAPTER 2: SURVEY METHODS

The first important step in determining the current state of a wreck and the impact it currently has (or may have) on the marine environment is to assess it based on previously gathered information on the state of other, similar wrecks (taking account of age, length, type, fuel volume etc.). These findings will be used to estimate the risk of fuel spill from the wreck.

The second important step consists of tests aimed at identifying the actual condition of the wreck and its surroundings, i.e. the wreck site. On the basis of detailed results of these tests, a review of the risk estimate made under the research conditions should be carried out. If it is decided that the wreck requires action, the obtained data will be used to plan the clean-up action and to assess its impact (after completing this step). These data reflect physical and chemical properties of the wreck and can be used later to assess the progress of the remediation process on the wreck and its surroundings.

When collecting this information, a certain data quality should be ensured. For this purpose, it is necessary to follow established procedures and proceed in a methodical and systemic manner. The need for such action is justified by the need to perform specific activities and tests in the following manner:

- **well-thought-out** –allowing to save time and reduce costs by adjusting the type, quantity and extent of the measurements,
- **repeatable** – allowing to execute the assessment of the wreck's condition and risks posed by it in a relatively fast and accurate way,
- **reliable** – a systemic approach reduces the risk of error and allows precise comparison with other shipwrecks investigated with the same method.

The assessment of wrecks on the basis of a structured, predetermined action plan enables a consistent approach to determining their environmental risks.

2.1 Determining the order and methods of data collection

In order to determine all parameters relevant to the assessment of a wreck and the risk posed by it the following actions should be carried out:

- **Desk-based review** i.e. research consisting of the examination of:
  - existing documents and information, such as technical data and shipbuilding designs,
  - descriptions and photographs of the ship and of the sinking (if any),
  - witness descriptions,
  - transport documents (bill of lading), port log records,
  - records in relevant archives, such as the Hydrographic Office, Maritime Administration, libraries, civil and military archives,
  - historical films, literature descriptions, e.g. in the internet, fora of enthusiasts and hobbyists etc.,
  - in the case of war wrecks, records relating to the transport of explosives, military equipment, fuel, other war material,
  - evidence gathered during diving operations carried out on the wreck, scientific studies, observation during free diving such as photographs, films, drawings, notes, samples of the sea bottom and cargo;

- **Conducting geophysical surveys**, potentially involving:
  - bathymetric surveys to determine the depth of the wreck and to assess the nature of the seabed,
  - sidescan sonar, circulating sonar or an acoustic camera surveys, in order to determine the parameters of the wreck and to identify other objects in the vicinity,
  - sea bottom surveys using an acoustic sub-bottom profiler (SBP) to detect objects covered with a sediment and to detect layers of contaminated sediments (with heavy diesel oil),
  - magnetometric survey of metal object distribution with a magnetic signature, such as parts of the hull, equipment, cargo scattered around the wreck;
- **Geological exploration of the seabed**:
  - collecting surface samples with a surface sampler e.g. Van Veen sampler, Boxkorer or other similar devices,
  - collecting core samples, usually 3 m long cores are sufficient,
  - analysis and tests of collected samples for the type of sediment and their capacity to absorb harmful substances;
- **Chemical tests of soil and near-bottom water**:
  - analysis of bottom sediment samples,
  - analysis of near-bottom water;
- **Biological and ecotoxicological tests of bottom sediment samples**, usually samples for these tests are taken from geological samples:
  - biological analysis:
    - analysis of benthos organisms,
    - analysis of progressive species of the 1st order,
    - analysis of progressive species of the 2nd order,
  - ecotoxicological analysis;
- **Obtaining hydrographic data /navigational data**;
- **Inspection carried out on the wreck** using Remote Operated Vehicles (ROVs):
  - executing film and photographical documentation,
  - executing measurements with the use of an acoustic camera and laser scanners,
  - sampling the sediments from accessible parts of the wreck,
  - measuring the thickness of the plating,
  - if possible, non-invasive test of the content of the tanks using reverse neutron dispersion analysis;
- **Collection and analysis of environmental data** other than chemical, biological and other parameters, such as:
  - intensity of navigation of small and large vessels,
  - distance from the wreck to waterways and navigation routes,
  - amount of fishing nets on the wreck,
  - military activities around the wreck,
  - strong storms,
  - fishing operation with trawl nets,
  - diving on the wreck,
  - other important factors which could influence the durability of the wreck.

2.2 Important steps in the wreck investigation, having an impact on the workload and the quality of acquired knowledge

The presented scope includes most well-known and accessible methods of investigating wrecks and the seabed. The results can be used to clearly and repetitively describe the current state of the investigated object. The essence of this methodology is to identify the possibilities and define the necessary scope of action.

2.2.1 Magnetometric and geoseismic tests

The exact approach can be tailored to each individual wreck and in many cases a number of the tests can be omitted or reduced. For example, when investigating a wreck which is preserved intact, without an indication that there are large quantities of scattered cargo or elements around the wreck, there is a clear rationale for omitting some of the more labour-intensive measurements such as magnetometric measurements and acoustic profiling. In such situations, bathymetric measurements and sonar survey should be sufficient to proceed, i.e. for the purpose of identifying safe sites for sampling sediments around the wreck. Measurements with the use of a sediment profiler may be used to decide whether to collect the cores with a vibrocorer or not. If the image from the acoustic sediment profiler does not show clear interlayering, it can be concluded that the seabed is homogenous and does not contain a layer potentially contaminated with fuel.

2.2.2 Geological, biological and ecotoxicological tests

Besides the sampling of the seabed for geological and chemical analysis, water near the bottom can also be sampled. The selection of sites for sampling seabed as well as water should take into account the place where the wreck is located. For example, if the wreck lies in a depression, it is recommended to take samples of the seabed and water from the bottom of this depression, because substances leaking from the wreck tend to accumulate there. The main directions of the currents near the bottom around the wreck should also be taken into account, because water carries bottom sediments (bed load) and substances leaking from the wreck along these directions. More than one sample of the seabed and water should be taken in these directions, at different distances from the wreck. It is best to perform an analysis of the currents using a model before the survey of the wreck starts, because it can later help in determining the sampling sites. If this is not possible, the results of the bottom bathymetry should be used. On the basis of the bottom morphology around the wreck an experienced hydrographer will immediately recognise how the bottom currents are arranged.

Sampling for biological and ecotoxicological tests is usually carried out at the same time, at the same site and using the same tool as geological testing, most often with the Van Veen sampler or boxcorer. It is an effective tool and when planning sampling with it, its size should be taken into account, to ensure enough material is gathered in a single sample for all necessary tests. If the sampler is small, two or even three samples of the seabed will have to be taken at one site. Both the biological and ecotoxicological sample tests are expensive, therefore it is worth considering whether to take samples for a biological test if the sample taken for geological tests is homogenous and consists of sand, in particular clean sand, without any characteristic smell of fuel or other substances not typical for the sea bottom. On the other hand, carrying out such a test is recommended because it quite well determines the purity of the seabed. The presence or absence of many benthos organisms characteristic for a given area in the sample may indicate that the sea bottom is clean or contaminated. Ecotoxicological tests are a very important indicator of the level and range of the contamination, however, these tests are expensive and worth carrying out only in the event of the confirmed presence of contaminants in the bottom sediments. Usually, these tests are carried out in the framework of extended surveys, before any wreck cleaning operation (mv Franken) or seabed remediation around the wreck (the case of S/S Stuttgart).

2.2.3 In situ observations and measurements (photographic, film and sonar documentation)

One of the important actions to be taken in any case, if possible, is a video inspection of the wreck. It can be done with submerged cameras or remotely-operated vehicles (ROV). ROV's are commonly used and experience shows that they are much more effective than lowered cameras. Photographs and films obtained with the use of the ROV will provide answers to many questions, such as:

- the state of the sides and superstructures,
- the presence of fishing nets on the wreck, their amount and type,
- the presence of munition and other explosives,
- visible damage,
- coverage of the wreck with bottom sediments,
- material around the wreck – such as scattered structural elements or cargo.

With the use of modern acoustic mapping technologies (MBES, SSS, acoustic cameras), it is possible to create spatial images. Latest technologies allow scanning with laser light or photogrammetric tessellation and it is now possible to create spatial visualisations of entire wrecks. It is also possible to combine construction plans (technical drawings and construction schemes used during the design process and ship construction) with 3D computer z visualisations and objects displayed in photographs taken by divers or ROV. The latest photogrammetric technology permits to make spatial models of objects (including large objects such as wrecks) from time-lapse photographs or directly from high quality films. Photographic materials used in this process should meet a number of conditions (relatively easy to fulfil):

- zdjęcia photographs should be taken at a sufficiently short distance from the wreck to catch all details, but not too close, in order not to increase the amount of collected data;
- a wide shot permits to make photographs of objects from different perspectives;
- consecutive images should be taken with a certain overlap, allowing the programme to find common points on subsequent shots – these points are essential to combine images;
- consecutive lines along which the camera recording the images moves, should be parallel (recommended but not obligatory) to guarantee a certain overlap.

The planning process and photographs require some experience and consistency due to the need to provide images of the same objects seen from different angles. This is not easy for divers to achieve, because the process is tedious to carry out and, as a consequence, the results they produce sometimes do not meet expectations (for example the Franken shipwreck). Making photographic documentation with an ROV is a better solution, because an ROV is not limited by diving time and does not get bored during the operation. However, there is high risk that the ROV may entangle in any elements emerging from the wreck, such as masts, floating ropes or fishing nets and in consequence may get lost. The choice of photo and video technology will depend on the current capacities of the entity conducting the survey, the depth at which the wreck is lying, its condition, obstacles located on the wreck and many other factors.

2.3 Other important information to be taken into account when investigating the wreck

2.3.1 Estimating the risk of fuel leakage at all stages of the procedure

The condition of the shipwrecks deteriorates rapidly with time and as a consequence the probability of contaminants escaping from a wreckage increases. Any potential spill poses a threat to the marine environment. As is clear from past events, such spills can also have socio-economic consequences. Therefore, one of the important elements of detailed wreck surveys, in terms of their impact on the environment and the economy of coastal regions, is a risk assessment associated with shipwrecks.

The methodology presented in this study focusses on proposing a general framework of such risk assessments. The risk assessment should take into account the current available knowledge about the wreck; physical, chemical and biological conditions at the time of the survey; as well as the conditions around the wreck (traffic, diving activities and others). The risk assessment should provide the research team with data to support the decision-making process related to the remedial actions, and thus permit effective use of available resources to reduce the possibility of an environmental catastrophe.

There are many methods of conducting risk assessments of wrecks. They differ in the assessment methodology, type of input data and the assessment of the level of impact of individual environmental factors on the wreck. However, all the available methods can be compared by referencing the results to the relevant parts of the international risk management standard. Such a comparison has been made by a scientific team from the Chalmers University in Goteborg (H. Landquist et al 2012). It suggested that the existing methods lack several key elements necessary for the risk assessment of shipwrecks. The team concluded that none of the assessed methods provide a complex risk assessment related to potentially polluting shipwrecks, and only a few include such factors as the uncertainty of data and sensitivity of the areas in the close vicinity to the wreck. It also demonstrated that **there is a need to develop a method of risk assessment that takes into account long-term effects of continuous releases of oil into the marine environment**. Finally, general, comprehensive framework of risk assessment related to shipwrecks was proposed. The risk assessment method proposed in this study takes into account the above-mentioned analyses and is based on the experience of its authors. Many of these reliable assessments have been described in the UK model used to estimate risk in the British Centre for Environment Fisheries & Aquaculture Science (CEFAS).

When analysing the current quantity and distribution of residual fuel in the wreck, a number of criteria specifying the potential possibility of retaining it in the enclosed spaces in the wreck should be taken into account. In defining the input parameters for a risk assessment of oil spills, it was assumed that the highest likelihood of detecting fuel in the wreck occurs when the wreck is in one piece, slightly lower when the wreck is broken in several parts and the lowest when the wreck is heavily damaged and does not constitute a recognisable structure. There are wrecks, such as S/S Stuttgart, which are no longer a one-piece structure, but the fuel that has previously leaked from it, pollutes a large area (in this case 415 thousand m^2 or even more).

2.3.2 Construction of the vessel and its impact on the fuel distribution

Except for the parameters mentioned above, there are also other criteria that need to be taken into account during the risk assessment, such as the type and construction of the vessel. In the case of a merchant vessel and a war ship, different construction and distribution of fuel tanks should be considered. This knowledge can be very practical and useful during data analysis aimed at assessing the risk of fuel deposition and the possible amount of fuel remaining in the tanks.

Cargo vessels have a simple construction and relatively few large fuel tanks. Usually there are 4-6 tanks with fuel needed for vessel's own use. The tanks are located in the hull of the ship. In addition, there is a tank under the engine room, service tanks in the engine room (one large tank for the main engine and power generating units or separate tanks for each engine and unit). Fuel is not the main medium used for ballasting this type of vessel. Water ballast tanks are used for this purpose. Usually, such vessels have properly secured, but relatively simple ventilation systems for each fuel tank. The vent systems have outputs on the deck. Due to their structure protected against water flow into the tank, but not protecting from fuel leakage from the tank, the check valves placed in the tank air valves are the main source of fuel leakage.

Warships, on the other hand, have a completely different structure. They are not intended for transporting cargo except for fuel, munition and combat supplies as well as supplies needed for the crew at sea. Therefore, the fuel system is much more complex. Often the fuel systems are duplicated and are also used to ballast the vessel. Due to high requirements in terms of resistance of vessels to damage during military operations, their fuel systems are composed of several, much smaller tanks, located along the entire hull. Each engine room is equipped with several tanks, smaller than on merchant vessels – mainly additional tanks used for pumping fuel during ballasting and for supplying each combustion engine (propulsion engine and power generating units). Each engine has its own fuel storage system in service tanks for current use. Ships (but also special units such as supply vessels, rescue vessels and others) have a very complicated air ventilation system, led through other tanks and fuel unit. An example of such vessels is the Franken wreck, which is partly a warship. Its fuel storage and supply system, as well as fuel vapour escape system are typical for such a ship. The system permits the fuel vapours to be safely discharged in a controlled manner, to a place where the risk of ignition (and explosion) is the lowest. Such solutions are used on ships using open fire during combat operations.

Constructing a large number of smaller tanks would constitute a problem on a merchant ship (as result of the tank's small volume), however, it is not considered to be a disadvantage on a war vessel. On the contrary, such fragmented system is viewed as an advantage since damage to a relatively small tank does not exclude the entire power system of the vessel from use. After cutting off the damaged tank from the system, the fuel is taken from other tanks. Flooding the damaged tank with water through the damaged hull does not affect the stability conditions of the vessel. The distribution of the tanks along the hull, on both sides, permits to take the fuel in such a way as to make them act as ballast tanks, allowing to maintain the trim and heel of the vessel within adequate limits. Of course, the war ships are equipped with a head unit to allow unrestricted management of fuel and safe, central venting of tanks.

Such a solution makes it possible to conclude that, in warship wrecks, fuel can be found not only in large tanks located on the sides or in a double-bottom and in engine rooms (as on merchant vessels), but practically in every part of the hull. The wreck of the Prinz Eugen heavy cruiser, cleaned from fuel by the American Navy in 2018, is a good example of such a vessel. During the cleaning operation, 867.000 litres of fuel was removed from 173 tanks or from separate, enclosed spaces where the fuel had accumulated[1]. Other warships, e.g. submarines, were also equipped with many fuel tanks (both outside and inside the hull). A good example is the German submarine VIIC, which could carry (depending on the version) from 57 to almost 100 tonnes of fuel, distributed in a dozen tanks of different sizes.

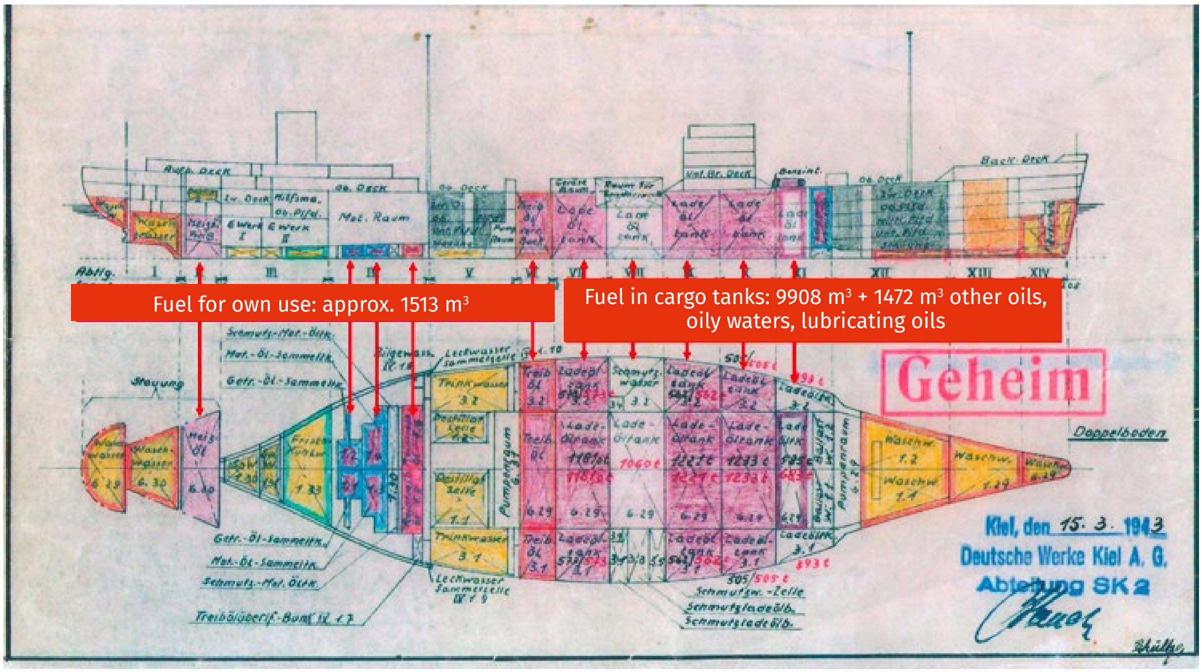


Figure 1. Scheme of fuel distribution on S/S Franken
(Source: Archives of Kriegsmarina Freiburg)

1 source: https://gcaptain.com/u-s-navy-salvage-team- completes-oil-removal-from-former-german-cruiser-prinz-eugen

It is difficult to imagine that a wreck of a merchant ship could contain an equally large number of tanks. An auxiliary vessel has both the characteristics of a merchant vessel (used to transport, among others, fuel) as well as characteristics of a warship. Once again, the Franken wreck is such an example. Apart from 19 tanks for transporting various kinds of hydrocarbons, it had additional 10 tanks (smaller than cargo tanks) for its own needs. It was equipped with a tank venting system and a fuel unit. As a result, even 75 years after sinking, some of the tanks may still be closed (containing fuel and sea water, filling the empty space). Due to the complicated fuel pipeline system inside the ship, the remaining fuel cannot freely leak. Based on that it can be assumed that there could still be approximately 1000 m^3 of hydrocarbons (fuel, oil, bilge water) in the Franken wreck. However, in reality, at the time of sinking the vessel was intensively exploited and certainly did not have a full possible fuel supply. Estimates suggest that the total load of fuel in the vessel amounted to 350-500 m^3. Research carried out on the wreck indicates that parts of cargo tanks are still closed and show no signs of leakage. This suggests that some of them may contain a certain amount of fuel or they might as well be empty. Further research is required to clarify this situation. Analyses carried out on the Franken shipwrecks also showed that several cargo tanks had become unsealed due to massive bomb explosions and burning fuel. However, this does not mean that they are empty and it is possible that each of them may still contain even a few dozen tonnes of fuel. This is due to the construction of the tanks. The current state of the wreck on the basis of research carried out on the Franken is illustrated in the Figure 2.

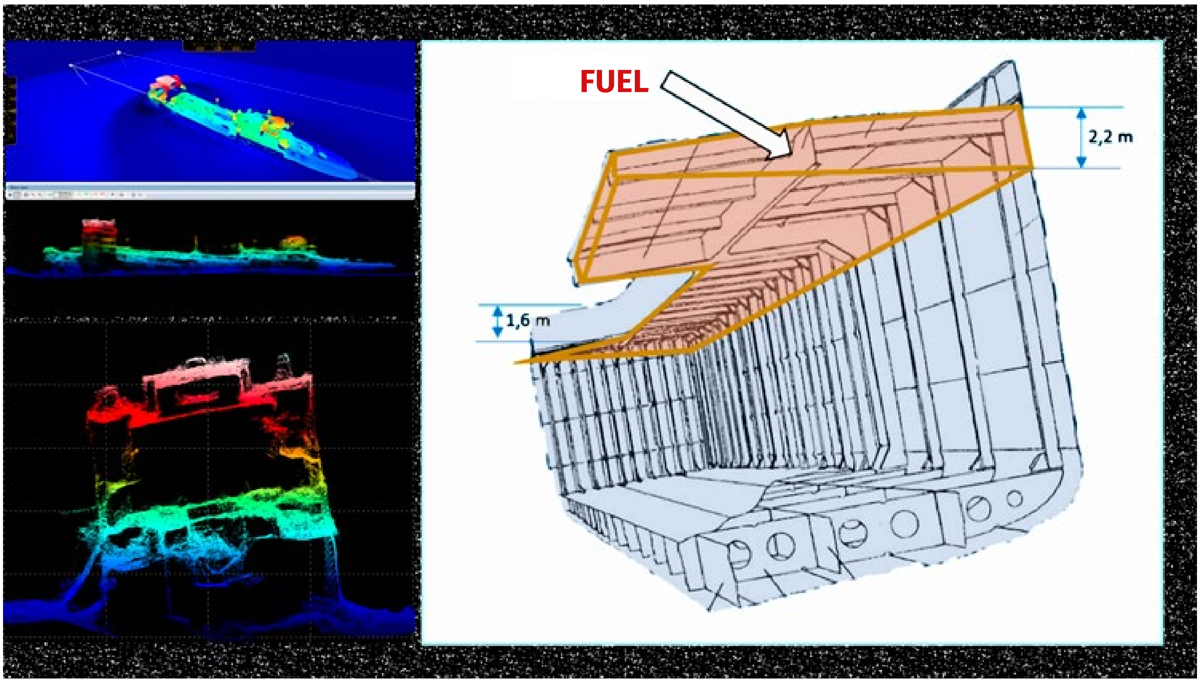


Figure 2. Fuel trapped in the cargo space of the Franken wreck in tanks with open hatches (Own source)

The structure of the hull and deck of the Franken wreck is very solid. Due to the vessel's size (178 m long, 22 m wide) the frames and deck beams, coamings and hatches are all very robust. The frames are approx. 160 cm high, coamings approx. 120-160 cm. As a result, after sinking, the fuel that is lighter than water, floats higher in the tanks closing it from the top. The fuel is trapped despite the fact that the hatches are open, especially in the situation observed in the Franken wreck, which stands slightly tilted on one of the sides. Assuming that the deck above the tank has a surface of approx. 100 m^2 (some tanks in Franken wreck had a deck surface up to 150 m^2), it is possible that 50-70 m^3 of fuel or even more might be deposited in such traps. There is a possible space for several such traps on the wreck.

2.4 Ammunition, unexploded mines, and other dangerous materials in the wreck

When estimating the risk, it is important to also take into account whether unexploded or abandoned ammunition, mines, deep-sea bombs, torpedoes, rockets, or other explosives are still located in the containers on the wreck. Very often the wrecks of war ships and cargo ships contain large amounts of such dangerous materials. Examples of such wrecks located in the Polish waters (in the Gdańsk Bay) are shown in the photos below.

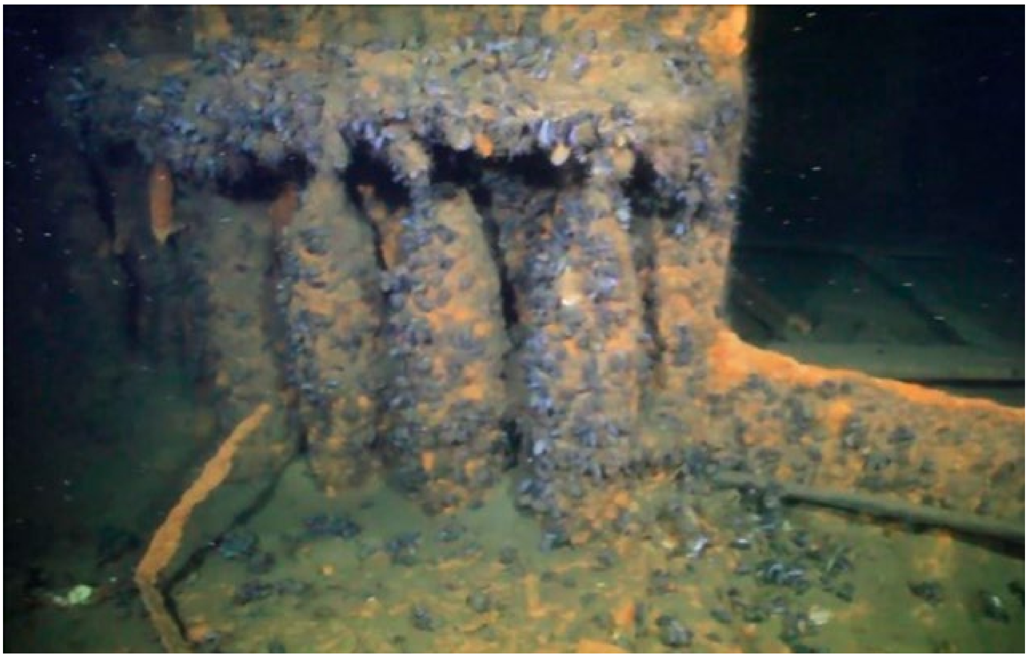
In many cases, the wreck cleaning operation must be preceded by removing unexploded ordnance. Their destruction on the spot is not possible, as this would cause an immediate, massive leakage from many tanks, possibly resulting in an ecological disaster. When estimating the risk associated with any operation on the wreck, it is necessary to make sure every time that there is no ammunition or other unexploded ordnance.

a)

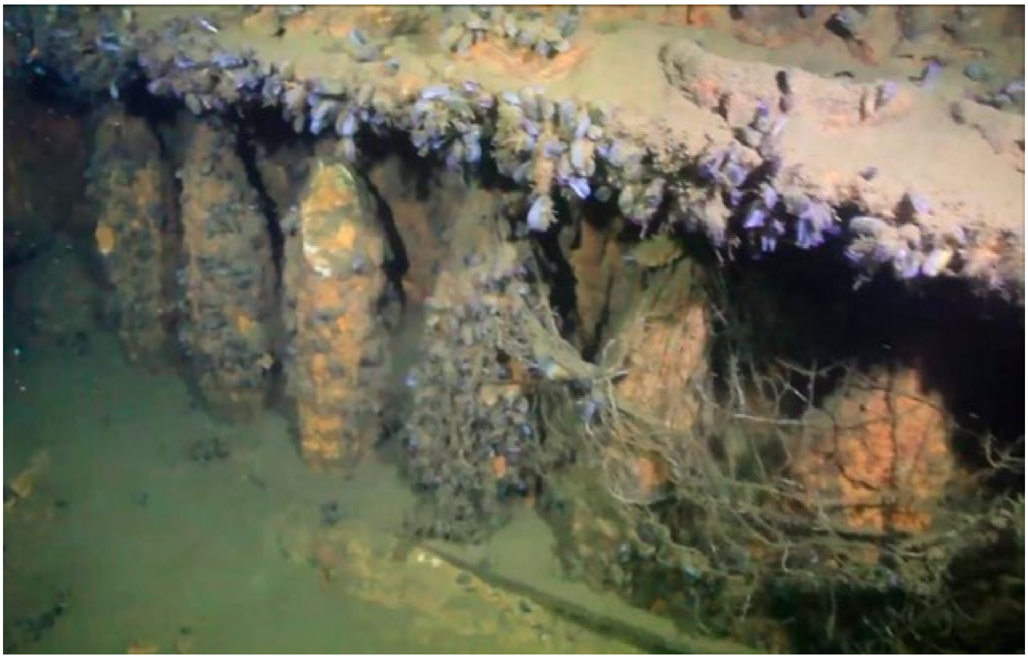
b)

Figure 3. Unexploded ordnance and ammunition on wrecks in the Gdańsk Bay:
a) and b) – deep-sea bombs on board of KFK-532 vessel; c) and d) –150 mm ammunition in the cannon emplacement on S/S Franken

c)



d)



CHAPTER 3: WRECK ENVIRONMENTAL RISK ASSESSMENT METHODS

In order to decide how best to manage wrecks, it is necessary to determine the extent of environmental risks they pose. Wrecks contain a variety of fuels, hazardous cargoes and munitions, but this study focuses solely on the risk of oil spills. Oil spill risk is a function of likelihood of oil release and its consequential environmental impact. Risk increases with time, but it can also be mitigated through active management techniques (Chapter 6).

The likelihood of oil release is initially determined from historical records, but should be supplemented by wreck survey data that indicates the physical integrity of the wreck, particularly its tanks. Potential environmental impact is estimated using oil spill models, with outputs presented as risk maps in the context of environmental (and perhaps socio-economic) sensitive receptors. Risk is thus determined by considering the sensitivity of potential receptors and the likelihood of their being impacted. The risks can be divided between the potentially affected areas, such as sea surface, water column, sediments and coastline.

The risk assessment and associated risk maps are useful tools for communicating the level of environmental danger posed by potentially polluting wrecks, and are also helpful during the process of requesting funding for risk management and remediation of contaminated areas. This chapter briefly describes the existing environmental risk assessments methods of wrecks and discusses in detail the two that seem the most relevant to the Baltic Sea region: the Environmental Desk-Based Assessment method (E-DBA) developed by the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) on behalf of the UK Ministry of Defence (this method is applicable globally), and the 'VRAKA' probabilistic risk assessment developed by Chalmers University of Technology in Gothenburg in Sweden that is applicable to wrecks in the Baltic Sea and parts of the North Sea.

3.1 Assessing the risk assessment methods of wrecks constituting a potential threat to the environment

Measures aimed at developing the right tools to support the decision-making process, have already been taken on several occasions – e.g. in the study by Terje Aven entitled *Foundations of risk analysis, a knowledge and decision-oriented perspective* (2003), where the description of the risk analysis is clearly linked to the description of ISO risk assessment (ISO, 2009). Aven proposes the basic structure of decision-making process – starting from defining the objectives, criteria and preferences, to making the final decision. Decision-making is therefore embedded in a framework in which risk analysis is intended as a tool to provide an important input to the decision-making process, although the final result is rarely fully predictable and known. Almost always the decisions need to be taken in uncertainty.

Risk management process usually consists of several stages. The first stage is to set the context, defining the scope and purpose of risk management. Next step is to carry out an assessment aimed at identifying all risk factors, which means identifying areas that the wreck has already impacted or which will be impacted in the future, as well as the risk sources such as chemical and biological factors, time and potential causes and consequences of oil spills. The assessment also includes an analysis of the risk itself in order to better understand it and to adapt the input data used for the subsequent final risk assessment process. The analysis involves qualitative or quantitative assessment of the levels of risk. It is also important to properly assess what risks should be considered and how to prioritize them. Such an assessment has to be made both in the initial stage of the process and later in the final stages. It must also include a comparison of possible alternative solutions to reduce the risk of oil spill. All of this is done to reduce the possibility of oil spillage and minimize the effects of any environmental hazards. Such detailed activities support the decision-makers in assessing the benefits and limitations of possible ways to reduce the risk (ISO, 2009).

Decision-making concerning wrecks could thus be regarded as the process supported by formal risk analysis combined with an assessment and review of the management strategies (Aven, 2003). The assessment of the type and degree of risk and decision-making process are closely linked together and this fact should be taken into account during the preparation of the risk analysis and general risk assessment methods.

3.1.1 General frames of risk management

Thus far, many scientific studies, as well as official government documents and reports on risk assessments have been produced, and can be used as the basis for assessing the existing methods and directions of further development of oil spill risk assessment conducted on shipwrecks. Unfortunately, the most important documents concerning wrecks, such as the International Convention on the Removal of Wrecks adopted in Nairobi (IMO, 2007 r.) and the IMO Guidelines for Safety Assessment (FSA) do not set detailed framework or guidelines for such wreck assessment systems.

Eight different methods for assessing the environmental risks posed by shipwrecks are used as part of the existing assessment systems. Each one deals with the assessment of risk to a different degree and uses a different level of detail. Below is a very short overview of documents describing each method:

- ***The Wreck Oil Removal Program***, implemented in the United States by the National Oceanic and Atmospheric Administration NOAA uses scientifically justified approach to oil removal and minimising the costs and risk of contamination posed by sunken commercial ships (NOAA, 2009);
- ***Potentially polluting wrecks in marine waters*** by Michel et al. (2005) published in the framework of the IOCS (International Oil Spill Conference), presents guidelines for assessing the consequences and risk of oil release from wrecks potentially polluting the marine environment. The aim of the report is to identify the principles for objective analysis of shipwrecks, using a methodology describing potential risks related to oil release and to provide measures to solve the problem;
- **DEEPP Project *(Development of European Guidelines for Potentially Polluting Shipwrecks),*** (Alcaro et al., 2007) aims at delivering criteria and guidelines for dealing with potential environmental risks posed by shipwrecks to European coastal states and national administrations;
- ***Norwegian Pollution Control Authority* (NPCA)** has identified shipwrecks as a priority. The project for establishing a wreck database was carried out in three steps: registration, priority classification and required action in order to get full picture of shipwrecks along the Norwegian coast;
- ***The South Pacific Regional Environment Program* (SPREP)** under which *the Pacific Ocean Pollution Prevention Programme* (PACPOL) has been developed and is being carried out, aims at determining the level of sea pollution caused by leakages from shipwrecks and at minimizing the damage caused by shipwrecks from the Second World War (SPREP and SOPAC, 2002);
- ***The risk of wrecks or the wreck of risk? The Greek paradigm*** (Konstantinos et al., 2009), published as part of the 2nd International Conference on Risk Analysis and Crisis Response, presents a strategy of risk analysis related to wreck accidents in Greek waters. It is based on formal safety assessment by IMO (2002) and includes oil release risk;
- **The Swedish model "VRAKA" (*Probabilistic risk assessment of shipwrecks*)** developed by a scientific team from the Chalmers University of Technology in Gothenburg, led by Hanna Landquist (2016), consists of two parts:
  - tools for estimating the probability of release of hazardous substances from shipwrecks,
  - methods of estimating the potential consequences of such an event.

The tool for estimating the probability of a release of hazardous substances from shipwrecks is a software based on a Microsoft Excel spreadsheet, which presents the results as e.g. a probability distribution and the expected amount of the hazardous substances to be released. The method of estimating the consequences of oil spills also provides the possibility of obtaining results at multiple levels depending on the available tools and resources. Risk evaluation, which is a third part of VRAKA method, is also possible but is not an integral part of the Excel based tool. Results obtained by VRAKA can be regarded as a support in the decision-making process and a part of the entire assessment regarding the possibilities of mitigating the results of catastrophes caused by shipwrecks polluting the marine waters;

- **The British risk assessment system called *Wreck assessment protocol – Environmental Desk Based Assessment* (E-DBA)** published in 2016 was developed by the scientific team from the Centre for Environment Fisheries & Agriculture Science (CEFAS) and is being implemented under the governance of the Ministry of Defence of the United Kingdom (MoD). The purpose of the protocol is to make a standardised risk assessment on the basis of using the already available environmental data.

After analysing several risk assessment methods, representing various approaches to the problem, as well as different ways of using numerical techniques in quantitative risk modelling, the E-DBA method seems to be the best, the simplest and at the same time the most effective one. Consequently, its implementation in the conditions of the southern Baltic seems to be the most advantageous.

The E-BDA method is extremely interesting and allows to estimate the size of the threat on a three-level risk scale (high, moderate, low) and asses the confidence level in risk assessment results, also on a three-level scale (high, moderate, low). The method takes into account two scenarios – an acute release and its impact on the environment, and a slow release and its long-term effects on the marine environment. Due to the standardised procedure and the use of a fixed assessment path, the wrecks can be prioritised in a given region in terms of the level of risk they might generate. The simple and comprehensive methodology, as well as a clear presentation of subsequent steps of the procedure, permit a relatively quick and precise oil release risk assessment and its impact on the environment. However, this method does not permit to make projections into the future and to assess the changes of the risk level in time, which is possible using the VRAKA method. Nevertheless, its clear and simple structure will be more convincing in situations when the maritime administration needs to be informed about the necessity to make management decisions regarding wrecks.

Therefore, a detailed description of this method is presented below. This method will constitute the framework for the risk assessment methodology of oil spills as proposed in this document for the Polish marine areas.

3.2 Overview of the Environmental Desk-Based Assessment (E-DBA)

The E-DBA (Goodsir et al., 2019) was developed by CEFAS in 2016 on behalf of the UK Ministry of Defence as means of standardising wreck risk assessments for efficient prioritisation of resources. The E-DBA uses the Oil Spill Contingency and Response model (OSCAR, Sintef) and open access global metocean data, so it can be applied globally, yet other models and metocean data can also be used. The E-DBA does not have a built-in environmental sensitivity data, but can be applied wherever such data is available or can be collected locally.

The E-DBA assesses the environmental risk associated with wrecks through a three-stage process :

- Predicting the likelihood of wreck releasing oil using available historical information and wreck survey data;
- Modelling acute and chronic oil spill scenarios to determine the likelihood of sensitive ecological and socio-economic receptors getting exposed to released oil;
- Determining the risk to each receptor based on the likelihood of exposure and potential impact.

3.2.1 Key definitions

The following is a list of key terms used in the process of examining the impact of wrecks on the marine environment and assessing the risk of leakage of hazardous substances into the ecosystem (based on Goodsir et al., 2016):

Acute release: a significant oil spill, for example of one entire tank, over a short duration, usually within a 24 h period.

Bentos: flora and fauna on the seabed and within the seabed sediments.

Chronic release: a continuous but slow release of oil, for example 1 liter/h, over an extended period of time, usually more than 48 hrs and sometimes many weeks or months.

Effects or Impacts: an estimation of a receptors' response to the hazard(s) to which they are exposed.

Exposure: a receptor encountering a specific hazard.

Hazard: an event or agent (biological, chemical or physical) that may lead to harm or cause adverse effects. Hazards can have magnitude, some of which might be acceptable and others not.

Most probable scenario: the oil release scenario deemed most likely to occur.

PEC (*Predicted Environmental Concentration*): the predicted concentration of pollutant, which is determined for each grid cell in the oil spill model.

PNEC (*Predicted No Effect Concentration*): the concentration at which no effect is predicted to be observed based on ecotoxicological testing data.

Probability: the likelihood that a given event will occur, which may be expressed as a percentage or equivalent fraction or ratio.

Receptors: ecological (e.g. protected areas, birds, mammals) or economic (e.g. beaches, infrastructure, shipping, fishing) entities that can be impacted by pollution.

Risk: the potential impact of a hazard multiplied by its likelihood (or probability) of occurrence.

Risk assessment: the formal process of evaluating risk.

Risk management: the process of minimising risks by putting controls or processes in place to reduce the likelihood of a hazard occurring and/or mitigating the impacts of that hazard. For example, the likelihood of a wreck leaking oil can be reduced by removing the oil in a controlled fashion, and the impacts of an oil spill can be mitigated by responding quickly and efficiently to collect the oil.

Stochastic simulations: the combination of multiple numerical oil spill simulations for the same oil spill scenario but initiated at different times and dates to encompass the seasonal and temporal variations in metocean conditions. The stochastic output gives an overall value for each model grid cell based on all data combined, including the probability of a cell being impacted by that oil spill scenario.

Thresholds: the concentration or thickness of pollutant that must be exceeded in each surface, water column or shoreline grid cell in order to be included in the stochastic results.

Uncertainty: the degree to which knowledge is limited (e.g. about the sensitivity of a receptor to a hazard or the factors which influence exposure). Uncertainty originates from randomness (aleatory uncertainty) and incomplete knowledge (epistemic uncertainty).

3.2.2 E-DBA Process diagram

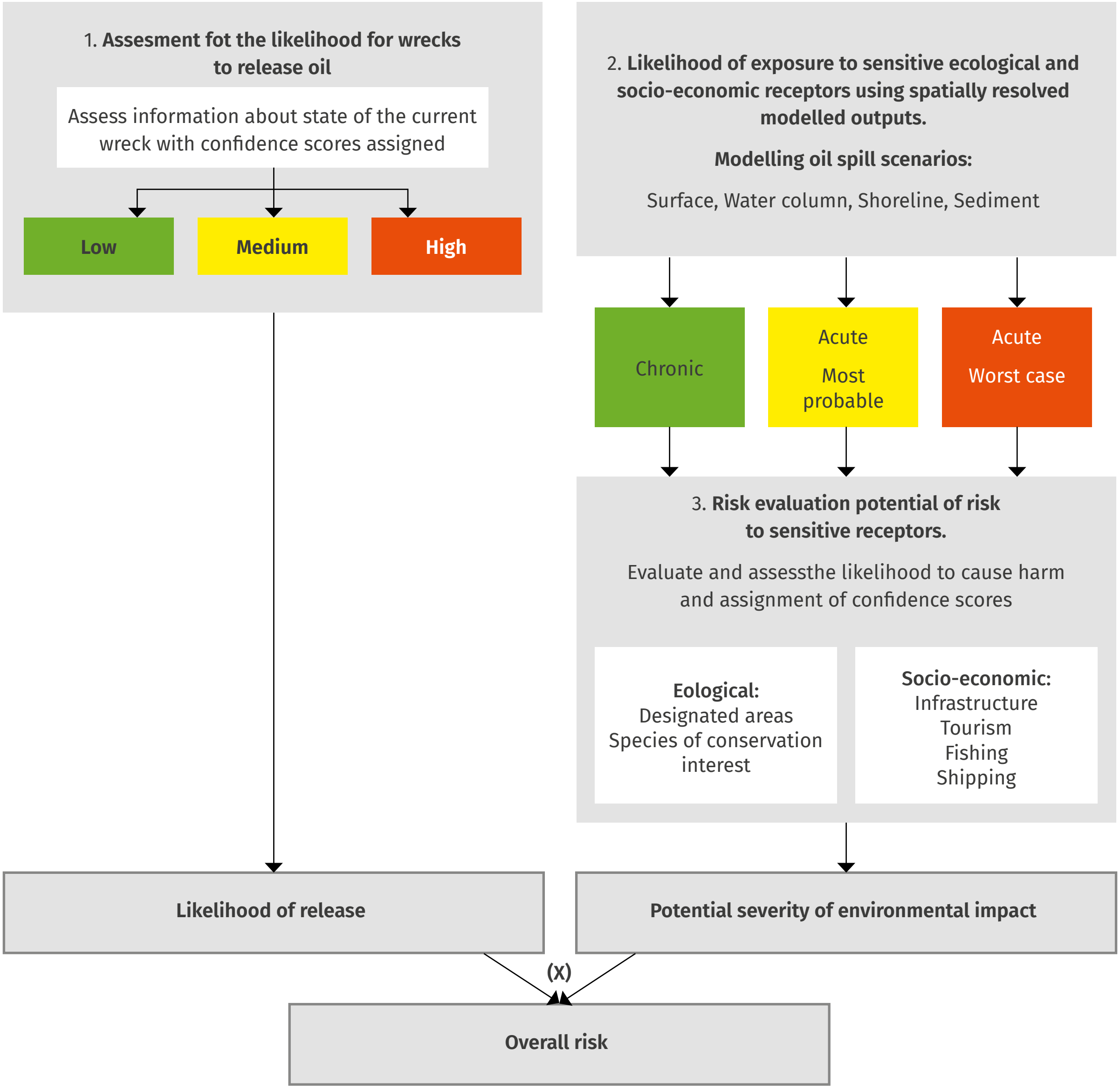


Figure 4. Flow diagram illustrating the assessment process for carrying out the environmental desk based assessment (E-DBA) for wrecks which the Ministry of Defence is responsible for
(Source: CEFAS Assessment Protocol Environmental Desk Based Assessment C6107)

3.2.3 Likelihood of oil release

The likelihood of oil release is assessed based on historical records (ship's plans, cargo and fuel inventories, cause of sinking, age and condition of the ship at the time of sinking, number of years since sinking), depth, seabed type, condition of wreck and history of oil releases. Each criterion is assessed as low, medium or high according to the definitions in Table 1. Some criteria are considered more important than others so, in accordance with ABP Marine Environmental Research Ltd (2007), each criterion is given a weighting of 1-3, with 3 being the most significant (table 1).

The overall likelihood of oil release scores is defined as follows:

- **Low (score <22)** – minimal risk of oil being released, but the wreck should be reassessed if its condition changes.
- **Medium (score 22-32)** – moderate risk of oil being released, but further analysis is recommended to understand the severity of the threat to sensitive marine receptors.
- **High (score >32)** – high risk of oil being released, detailed analysis is required to understand the severity of the threat to sensitive marine receptors.

Table 1. **Criteria for assessing the likelihood of oil release from wrecks**
(Source: CEFAS Assessment Protocol Environmental Desk Based Assessment C6107)

Risk assessment criteria	Weighting of criteria	**Low** (score of 1)	**Medium** (score of 2)	**High** (score of 3)
Vessel depth	2	low >100 m	30-100 m	high <30 m
History of leaks	3	no known leaks	unknown or anecdotal evidence	documented history of leaks
Integrity of wreck	2	broken into more than three pieces	broken into two or three pieces	intact, in one piece or unknown
Age of vessel at time of sinking	1	<10 years	10-30 years	>30 years
Length of time vessel has been submerged	2	<50 years	50-90 years	>90 years
Method of storage	2	specific bunker tank	in hold	on deck, drums, containers, crates
Type of incident causing sinking	1	multiple torpedo detonations, multiple mines, severe explosion	single torpedo, shellfire, single mine, rupture of hull, breaking in half, grounding on rocky shoreline or unknown	foul weather, grounding on soft bottom, collision
Seabed type	2	known to be stable seabed	relatively stable or not known	unstable and/or high degree of movement

Confidence in the information (its accuracy and usefulness), on the basis of which the assessment of the wreck's condition is made, is defined somewhat differently:

- **High** – the data and information used are timely, the best available, solid and the outputs are well supported by evidence. There is consensus amongst experts.
- **Medium** – the data and information is based on limited evidence or proxy information. There is a majority agreement between experts; but conflicting evidence/opposing views exist.
- **Low** – the data and information is limited and is not well supported by evidence. There is no clear agreement amongst experts.

When assessing the risk level of oil release, the sum of all weightings for each assessment category is used. In the case of confidence scores (included in the table) a 3-level scale is used. High confidence information receives a score of 3, whereas low confidence data a score of 1.

Table 2. **Scores for the most significant criteria of wreck assessment**
(Source: CEFAS Assessment Protocol Environmental Desk Based Assessment C6107)

Risk of oil release	Score	Confidence to data	Score
Low	<22	Low	8-12
Medium	22-24	Medium	13-19
High	>32	High	20-24

The methods of calculating and using different criteria are presented in the table 3, in which the available information on the RFA War Mehtar wreck, investigated by CEFAS, has been gathered.

Table 3. **Oil release likelihood assessment scoring based on eight criteria with a confidence score for each category, using the RFA *War Mehtar* wreck as an example**
(Source: CEFAS Assessment Protocol Environmental Desk Based Assessment C6107)

Risk assessment criteria	Risk category evidence for assigning risk	Weighted score = weighting × risk score	Confidence category level of confidence in data	Confidence score
Vessel depth	Between 26.5 m and 40 m with 2-3 m scour.	6	Recent detailed survey by ADUS confirmed depth (Lawrence et al., 2014).	3
History of leaks	Reported presence of oil patches 5-10m diameter on the surface. Oil tank Nos. 4, 5, 6 and 7 may have been ruptured. Report suggests it is unlikely that oil didn't escape from the vessel considering the damage.	6	The reports indicate there are no known leaks, however, the presence of patches of oil on the surface of the water has been reported, along with the smell of oil, indicating oil is still present on board.	2
Integrity of wreck	Broken in two just forward of her mid ships section. Lying on its port side Aft appears to have sunk into the seabed or collapsed.	4	Recent detailed survey by ADUS confirmed condition (Lawrence et al., 2014).	3
Age of vessel at time of sinking	21 years (in 2025 this will become high risk).	2	Construction date and date the vessel sunk are available.	3
Length of time vessel has been submerged	75 years (in 2031 this will become high risk).	4	The date the vessel sunk is available.	3
Method of storage	Two large dry cargo holds, seven cargo tanks for carriage of oil.	2	The reports indicate clearly that there are cargo tanks which have the purpose of holding oil.	3

Type of incident causing sinking	The vessel was hit by a torpedo, damaging the engine room bulkhead, explosion which ignited a flare of oil. Sank whilst undertow.	2	The captains report suggests the vessel was hit by a torpedo, the location of where this hit is not entirely clear. Clear evidence of torpedo damage to the port side (Lawrence et al., 2014).	3
Seabed type	A wreck lies in an area of significant tidal action. Scour and bed forms suggest sand sediments.	6	There is evidence from the multi-beam echosounder survey data of scour, which suggests soft sediments which may have a high degree of movement.	3
	Sum total of weighted risk scores	**32**	**Sum total of confidence scores**	**23**

3.2.4 Oil release modelling

The second step consist of assessing the exposure of the marine environment and infrastructure to the released fuel. Three scenarios for oil release are considered:

- Scenario of slow, but chronic release of oil, up to 50 kg per day.
- The most likely scenario of acute release of the entire oil content from the largest tank in 24 hours. (Unless stated elsewhere, tank volume is determined from ship's general assembly plans. In the absence of the wreck's own plans, plans from sister ships or similar should be used with caution. If there is no detailed information about the size of the tanks, it is assumed that it will be at least 10% of the total oil volume);
- The worst-case scenario, assuming the release of the entire oil content from the wreck within 24 hour.

Simulations of oil releases from the wreck are the next important step. Modelling permits to understand how the oil will flow in the water column, on the surface and at the sea bottom. Computer models constructed specifically for this purpose (CEFAS, VRAKA) are used for modelling or for simulating oil spills by government and life-saving services and in the framework of search and rescue operations (SAR). In Poland SAR uses the Swedish model (SeaTrack Web), estimating oil spills in the Baltic.

Various scenarios examine different options of oil release and estimate the risk of contamination of water surface, water column, sediment and shoreline. Models are used to calculate all scenarios except for the most acute scenario, as it is highly unlikely that the entire volume of oil from the wreck will be released at once. This assumption is also used in the presented E-BDA method.

For each wreck assessment, the chronic scenario is modelled using the *Dose-related Risk and Effects Assessment Model* (DREAM). The acute scenarios are modelled using the *Oil Spill Contingency and Response* (OSCAR) component of *Marine Environmental Modelling Workbench* (MEMW; SINTEF). The MEMW is the main tool used for emergency response and chemical releases in the marine environment in the territorial waters and economic zone of the UK. This modern model for surface and subsurface releases is an industry standard and one of only two commercially available models with the ability to model substance releases at depth (>400 m). The model includes water column stratification and separate sub-models for the tracking of gas bubbles, clathrates formation, oil weathering, biodegradation and sediment processes, and includes an extensive oil database (to which new oils and combinations of compounds can be added, such as carbon liquids [synthetic fuels] obtained in the Fischer-Tropsch process). It is a suitable tool for simulating both acute and chronic releases, at the surface or at depth. MEMW is an advanced model depicting the course of the event, taking into account the chemical processes occurring in the fuel, based on external forcing environmental conditions, such as currents and wind. The quality and accuracy of these environmental forcing factors, in turn, determines the reliability of the model results.

OSCAR and DREAM models do not contain routine procedure for determining the aerial dispersion of volatile substances, but take into account the amount of evaporated fuel. Each of the scenarios requires setting up release parameters, including the site position, amount and type of released substance, followed by the specification of the modelled domain, including 3D grids setup, and the provision of environmental forcing (currents and winds) data.

Each of the discussed models requires the provision of a specific number and types of input data that feed the model and allow for the development of the expected answer to the key questions, i.e.:

What will happen as a result of the leak and what will be the consequences?

The input data is presented below:

1. **Model domain** – usually a 30-day model duration is considered and therefore, a default model domain of 500 km by 500 km is used for each wreck.
2. **Position of the wreck** – is the wreck position or the last known location of the ship (for recent sinking). The release depth is set to 2 m above the seabed.
3. **Oil type** – the oil type is determined from available wreck reports (provided by Wessex Archaeology), where this is not available, proxies are used based on information regarding prevalent oils used on the vessel at the time of sinking (Brown, 2003; Environmental Technology Centre, 2016). This applies to oils with very different kinematic viscosities, ranging from very low viscosity fuels (from light Marine Diesel Oil, Marine Gas Oil to highly viscous residual fuels like Heavy Fuel Oil with a much higher density than water). Where the oil type is unknown from the wreck reports, the most appropriate oil is determined based on the vessel type and year of sinking. The oil type will be described in the site-specific Wreck Assessments.
4. **Currents** – velocity and direction of currents are used from the Copernicus model (http://marine.copernicus.eu/), and UK Met Office FOAM AMM7 model (Forecasting Ocean Assimilation Model 7 km Atlantic Margin model).
5. **Winds** – wind data are taken from the UKMO Euro4 atmospheric model with a 12 km horizontal resolution, the same spatial resolution as the Copernicus data.
6. **Duration** – the duration of the chronic and acute simulations is set to 30 days. For most wrecks 30 days provides ample time for the fates of the release to become steady, following an acute oil release. This occurs through a combination of evaporation, reaching the shore, sedimentation, and biodegradation, with small amounts of oil remaining on the sea surface and in the water column at the end of the simulation.
7. **Other input data**:
   - suspended sediment
   - settling velocity
   - oxygen content
   - temperature and salinity profile.

CEFAS bases its calculations on two models:

1. **DREAM, a model for slow but chronic release of oil** – a chemical dispersion model that uses wind and 3D current data to model how a discharge or spill disperses in the water column. Using knowledge on physiochemical properties and biodegradability it calculates the Predicted Environmental Concentration (PEC) of the discharge. The model produces an assessment of the risk in relation to marine species.
2. **Acute oil release model MEMW together with the OSCAR response component** – these tools allow to determine the method and changes during the ongoing leak, taking into account water movement and hydrometeorological conditions. Since these processes are very acute and unpredictable,

random processes are modelled, taking into account a number of additional factors that have a significant impact on the way fuel spills during an acute release.

The following thresholds are used between a slow and acute release:

- contamination of the shoreline of 50 kg/km (this corresponds to 1 g/m^2 under the assumption that the shore is 50 m wide),
- contamination of the sea surface at the level of 0.1 t/km^2 or 0.1 g/m^2 (this is an equivalent to a 0.1 µm thick layer, where sheen will start to be visible),
- contamination of water column at the level of 50 ppm (total concentration at the level of 50 ppb is the threshold concentration for the most toxic components in water, considered as dangerous).

Both models permit to calculate the contamination risk and in addition generate valuable information on:

- **shoreline**: probability of contamination above the threshold, minimum arrival time, maximum accumulated oil mass;
- **sea surface**: probability of contamination above the threshold, maximum exposure time, maximum time-averaged oil mass;
- **water column**: probability of contamination above the threshold, maximum exposure time, maximum time-averaged total concentration of oil in the water.

The E-BDA tool is also used for modelling the contamination of sediments around wrecks. Simulations are performed to calculate the sediment deposition on the seabed. It is possible to assess whether the sediments intended for removal are contaminated to an extent that poses a risk to the environment. CEFAS Wreck Assessment Protocol V6 presents the contamination exceedance thresholds.

The presented models permit to generate release maps of the oil release from a wreck. The maps show:

- the potential area at risk of fuel spills on the sea surface – in the event of an acute release of substances from the wreck;
- the potential area at risk of water column contamination;
- the potential area at risk of oil reaching the shoreline;
- the potential area of accumulation of oil heavier than water in the sediments surrounding the wreck.

3.2.5 Quantification of risk for sensitive areas and selected environmental receptors

The third step in estimating the threat posed by a given wreck as a result of the release of hazardous substances, consists of risk evaluation of negative impact of the released oil on particularly sensitive receptors and marine infrastructure. Two areas of influence are considered:

1. **Ecological sensitive marine receptors**:
   - coastal and marine protected areas (to protect biological resources),
   - marine mammals (cetaceans, porpoises, seals),
   - birds,
   - fish (nursery and spawning grounds),
   - benthos communities.
2. **Socio-economic sensitive marine receptors**:
   - infrastructure at sea (wind farms, mining installations, water intakes for industry e.g. nuclear power plants, aquaculture, ports etc.)
   - tourism in recreational areas along the shore, diving, kitesurfing

- demersal, pelagic fishery and crustaceans,
- shipping,
- others – e.g. protected wrecks.

Information on where and what receptors are located in areas governed by maritime administration are collected through an analysis of available sources, i.e. by analysing spatial management plans, environmental permissions and economic studies prior to investments etc.

CEFAS uses a 3-level classification of receptors according to their sensitivity to low risk, medium risk and high risk of contamination. However, a different **PEC (predicted environmental concentration) / PNEC (predicted no effect concentration)** ratio level may be set for each type of receptor.

The risk to marine areas, where living organisms occur, is estimated according to following criteria:

Low risk < 0.2	Medium risk 0.2 – 1.0	High risk >1.0

For birds (in particular those sensitive to oil) the criteria are somewhat different:

Low risk < 0,002	Medium risk 0,002 – 0,2	High risk >0,2

This creates the possibility to systematise partial risks in a useful way to calculate the final risk.

Table 4. **Classification of the sensitive ecological marine receptors to a chronic oil release (for PEC/PNEC values)** (Source: CEFAS Assessment Protocol Environmental Desk Based Assessment C6107)

Risk assessment criteria	Relevant oil spill model (shoreline, sea surface, water column or sediment)	**Low** (score as 1)	**Medium** (score as 2)	**High** (score as 3)
Coastal and marine protected areas	water column, sediment, sea surface and shoreline	< 0,002	0,002-0,2	> 0,2
Species and features of conservation interest				
Marine mammals (seals)	water column, sea surface and shoreline	< 0,2	0,2-1	>1
Marine mammals (cetaceans and sirenians)	water column and sea surface	< 0,2	0,2-1	>1
Marine Reptiles	water column, sea surface and shoreline	<0,2	0,2-1	>1
Seabirds	sea surface and shoreline	<0,002	0,002-0,2	>0,2
Benthic features and species including designated shellfish grounds	water column and sediment	Predicted total footprint of oil deposition on sediment <100 km^2 and <0.002 PEC/PNEC risk of any overlap with protected benthic features and species.	Predicted total footprint of oil deposition on sediment between 100-1 000 km^2 or 0.002-0.2 PEC/PNEC risk of any overlap with protected benthic features and species.	Predicted total footprint of oil deposition on sediment >1 000 km^2 or >0.2 PEC/PNEC risk of any overlap with protected benthic features and species.
Fish spawning and nursery areas	water column and sediment	No known spawning or nursery areas.	Oil spill interacts with known discrete areas used for spawning and/or nursery area.	Oil spill interacts with high intensity spawning and/or nursery areas.
Fish (sensitive or charismatic species)	water column and sediment	No known species.	Oil spill interacts with known discrete areas used by sensitive or charismatic species.	Oil spill interacts with area used by large numbers of sensitive or charismatic species.

Table 5. **Classification of the socio-economic sensitive marine receptors to a chronic oil release**
(Source: CEFAS Assessment Protocol Environmental Desk Based Assessment C6107)

Risk assessment criteria	Relevant oil spill model (Shoreline, Sea surface, Water column or Sediment)	**Low** (Score as 1)	**Medium** (Score as 2)	**High** (Score as 3)
Current and planned infrastructure				
Offshore wind farms	Sea surface	No overlap of sea surface oil with any windfarm.	Seasonal overlap of sea surface oil at a concentration above the threshold for more than 5% of a windfarm lease area.	Year round overlap of sea surface oil at a concentration above the threshold for more than 5% of a windfarm lease area.
Offshore oil and gas installations	Sea surface	No overlap of sea surface oil with any installation.	Seasonal overlap of sea surface oil at a concentration above the threshold for any installation.	Year round overlap of sea surface oil at a concentration above the threshold for any installation.
Industrial water intakes	Shoreline	No overlap with any industrial water intake.	Seasonal overlap at a concentration above the threshold with any industrial water intake.	Year round overlap at a concentration above the threshold with any industrial water intake.
Aquaculture	Water column and sea surface	No overlap with any aquaculture facility.	Seasonal overlap at a concentration above the threshold with any aquaculture facility.	Year round overlap at a concentration above the threshold with any aquacultu-re facility.
Tourism and leisure areas				
Tourism	Shoreline	No overlap with any known tourist areas impacted.	Seasonal overlap at a concentration above the threshold of any known tourist areas impacted.	Year round overlap at a concentration above the threshold of any known tourist areas impacted.
High use areas	Shoreline	No overlap with any high use are-as.	Seasonal overlap at a concentration above the threshold with any high use areas.	Year round overlap at a concentration above the threshold with any high use areas.

Risk assessment criteria	Relevant oil spill model (Shoreline, Sea surface, Water column or Sediment)	**Low** (Score as 1)	**Medium** (Score as 2)	**High** (Score as 3)
Fishing grounds				
Demersal	Sediment and sea surface	<180 days of fishing effort impacted in area of oil contamination occurring.	180-365 days of fishing effort impacted in area of oil contamination occurring.	>365 days of fishing effort impacted in area of oil contamination occurring.
Pelagic	Water column and sea surface	<180 days of fishing effort impacted in area of oil contamination occurring.	180-365 days of fishing effort impacted in area of oil contamination occurring.	>365 days of fishing effort impacted in area of oil contamination occurring.
Crustacean	Sediment and sea surface	<180 days of fishing effort impacted in area of oil contamination occurring.	180-365 days of fishing effort impacted in area of oil contamination occurring.	>365 days of fishing effort impacted in area of oil contamination occurring.
Shipping				
Important shipping lanes	Sea surface	No overlap with any important shipping lanes.	Seasonal overlap at a concentration above the threshold with any important shipping lanes.	Year round overlap at a concentration above the threshold with any important shipping lanes.
Ports	Shoreline	No overlap with any ports.	Seasonal overlap at a concentration above the threshold with any ports.	Year round overlap at a concentration above the threshold with any ports.

Similar criteria but differently specified, were defined and tabled for acute releases. The main criteria for acute release was the area covered with oil to the total impacted area. The following criteria were adopted:

Low risk < 5%	Medium risk 5% – 50%	High risk >50%

3.2.6 Final risk score

The final calculation of risk qualifying the wreck as hazardous or safe for the environment is done based on the probability of a hazardous substance release and the risk posed by such an event to sensitive marine receptors. Each criteria is assigned a point value of likelihood and risk from 1 to 3, based on a high/medium/low score (H=3, M=2, L=1), using the following method:

Final ecological risk assessment score =
likelihood of release x ecological risk

Final socio-economic risk assessment score =
likelihood of release x socio-economic risk

Final ecological risk assessment score		Final socio-economic risk assessment score	
Score min = 90 Score max = 810	Low risk <240	Score min = 60 Score max = 540	Low risk <160
	Medium risk 240-360		Medium risk 160-240
	High risk >360		High risk >240

3.2.7 Calculating confidence score

In order to clearly determine whether the risk assessment is reliable and whether it was done in the best possible way and the results are close to the truth, it is essential to use robust data, collected according to the established rules, and to make sure that there are no significant discrepancies among experts involved in the assessment.

The confidence score is calculated using three thresholds:

High confidence >80%	Medium confidence 50 – 80%	Low confidence<50%

The estimated risk level corresponds to the percentage score in the overall risk assessment that was based on objective measurements or data estimated with high confidence score. However, there is often no such data and the risk assessment is based on experience and knowledge of experts conducing the assessment. This information can be acquired during the survey of other wrecks and other release scenarios.

Therefore, it should be assumed that, despite the best efforts, the confidence level is largely biased, because the assessment is made by people and although it is mainly based on real indicators, some occurrences are assessed subjectively. Despite these limitations, however, the confidence score plays an important role at the final stage of the assessment process. Since the amount of data obtained through the subjective perception of those involved in the assessment is finite (or relatively little), such uncertainty needs to be accepted, because so far, there is no better way to assess the risk.

In the Assessment Protocol Environmental Desk-Based Assessment C6107, CEFAS shows how to calculate (estimate) the confidence level in the estimated risk, based on the example of a selected wreck. The main objective of the actions presented so far is to answer the following question:

„Does the wreck pose a threat and is it necessary to take any actions aimed at mitigating the risk of a spill"?

To this end, it is recommended to introduce a more detailed and more precise classification of the criteria for general risk assessment as presented in Table 6:

Table 6. **Detailed classification of general risk assessment criteria**

CRITERIA FOR THE OVERALL ASSESSMENT OF RISK		
High risk	**Medium risk**	**Low risk**
There is a high potential for oil to be released. Detailed analysis is required to understand the severity of the threat to sensitive marine receptors.	The risk of oil being released is moderate. Further analysis is recommended to understand the severity of the threat to sensitive marine receptors.	The risk of oil being released is minimal. If the condition of a wreck changes a re-assessment is recommended to confirm risk.
RECOMMENDED ACTIONS		
Assessment has shown that there is a considerable threat to sensitive marine receptors, essential management actions will need to be considered.	The assessment has shown there is a threat to sensitive marine receptors, monitoring and that management may be required.	If the condition of a wreck changes a re-assessment is recommended to confirm risk. Monitoring may be required.

The following definitions can be used for overall confidence assessment:

DEFINITIONS OF CONFIDENCE LEVELS IN THE RISK ASSESSMENT PROCESS		
High confidence	**Medium confidence**	**Low confidence**
The data and information used are timely, the best available, robust and the outputs are well supported by evidence. There is consensus amongst experts.	The data and information is based on limited evidence and or proxy information. There is a majority agreement between experts; but conflicting evidence/ opposing views exist.	The data and information is limited and is not well supported by evidence. There is no clear agreement amongst experts.

3.3 Risk assessment methodology for Polish wrecks

As already stated, the E-DBA protocol developed by CEFAS seems to the most appropriate to adapt for the assessment of Polish wrecks in the Baltic waters. It does not assess how risk changes with time, which is possible using the VRAKA method, but it has a clear and simple structure. A Polish version of the E-BDA would provide an impartial assessment of risk and determine the most appropriate management strategy, thereby minimising conflict of interests with the maritime administration, who would be consulted throughout the assessment process.

The proposed methodology for wreck risk assessments is based on the following principles:

- All wrecks should be subject to the risk assessment, based on potential risk of contamination and presence of explosives, ammunition or other hazardous substances. This assessment should be based on the wreck database and supplemented by other reliable sources.
- Based on the risk assessment, wrecks are classified one of the four risk categories:
  - **dangerous wrecks**, for which the risk cannot be tolerated and a wreck site survey is required to gather data for a more robust risk assessment.
  - **potentially dangerous wrecks**, for which the risk can be tolerated, but a wreck management plan is required.
  - **probably non-dangerous wrecks**, for which the risk can be tolerated, but the “risk should be as low as possible”.
  - **probably safe wrecks**, for which the risk can be tolerated and there is no need to demonstrate the risk status.
- If there is no sufficient information to consider a wreck survey as reliable, then the wreck should be considered as dangerous or potentially dangerous and appropriate actions should be taken.

As is done in the E-DBA, the following factors should be taken into account when assessing the risk posed by wrecks:

- amount and type of fuel on board the vessel at the time of sinking,
- amount of explosives on board the vessel at the time of sinking,
- cargo and hazardous substances inside the wreck,
- historic value of the wreck,
- weather conditions, currents and other hydrological data,
- water depth around the wreck,
- invasive human impact (trawling, military training grounds),
- proximity of:
  - ecologically sensitive areas, including areas of special scientific importance,
  - protected areas and special areas of conservation,
  - densely populated areas,
  - areas with recreational and tourist activities,
  - areas with trade activities,
  - areas with heavy shipping traffic with significant traffic of large ships,
  - cultural heritage sites.

On-site surveys of the wreck should be carried out as described in the Chapter 4: *Methodology for conducting geophysical surveys*. The scope of the survey must be adapted to the risks identified with the particular wreck. A report should be prepared after a review on-site and it will later be used to reassess the risk and determine the risk category of the wreck. If the survey and reassessment of risk category show that the wreck poses a risk (is classified in the first two categories), a risk management plan in an event of an acute release of oil should be prepared. It should contain detailed information on the measures to be taken to manage the risk. The level of detail of this plan should be proportionate to the level of risk associated with the wreck.

If an on-site survey of the wreck and reassessment of the risk show that the risk is unacceptably high and, most probably, cannot be managed, an action on the wreck is required. This action is aimed at minimising the risk of uncontrolled release of fuel. Therefore, a methodology for dealing with such a situation is required. Examples of such procedures are included in the Chapter 5: *Review of available methods and technologies for removing fuel from shipwrecks and remediating the contaminated sediments*. The resulting methodology must be adapted to the specific wreck. Removing a potential risk from the wreck is a preferred risk mitigation measure. After the actions on the wreck are conducted, another risk assessment should be carried out. In all cases, after the action, another risk management plan should be prepared. This should be done even if the risk has been mitigated to an acceptable level.

The algorithm for conducting the examination of wrecks in terms for risks and threats they pose to the environment, is presented below. The procedure shows the steps to be taken to obtain as complete and comprehensive information as possible about the current situation on and around the wreck, as well as to precisely (as far as possible) assess the type and level of the risk.

Algorithm 1. **Steps to be taken during the study of wrecks in terms of risks and threats to the environment**

Environmental impact assessment of wrecks

Long-term and chronic release of oil from a wreck

Instantaneous, acute oil release from a wreck

Assessing the likelihood of oil release from wrecks

Information of the assessment of the current state of a wreck with confidence scores

Risk assessment criteria	Weighting of criteria	**Low** (score of 1)	**Medium** (score of 2)	**High** (score of 3)
Vessel depth	2	low >100 m	30-100 m	high <30 m
History of leaks	3	no known leaks	unknown or anecdotal evidence	documented history of leaks
Integrity of wreck	2	broken into more than three pieces	broken into two or three pieces	intact, in one piece or unknown
Age of vessel at time of sinking	1	<10 years	10-30 years	>30 years
Length of time vessel has been submerged	2	<50 years	50-90 years	>90 years
Method of storage	2	specific bunker tank	in hold	on deck, drums, containers, crates
Type of incident causing sinking	1	multiple torpedo detonations, multiple mines, severe explosion	single torpedo, shellfire, single mine, rupture of hull, breaking in half, grounding on rocky shoreline or unknown	foul weather, grounding on soft bottom, collision
Seabed type	2	known to be stable seabed	relatively stable or not known	unstable and/or high degree of movement

Risk of oil release
Sum of all weightings for each criteria (weighting criterium and weighting)

Risk of oil release	Score
Low	**< 22**
Medium	**22-24**
High	**> 32**

Confidence to data
Sum of all weightings for each criteria (assessment criteria x confidence weighting)

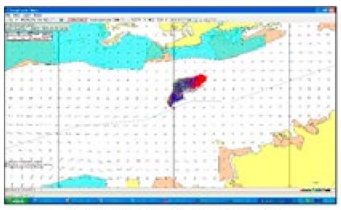
Confidence to data	Score
Low	**8-12**
Medium	**13-19**
High	**20-24**

Modelling oil release/spill

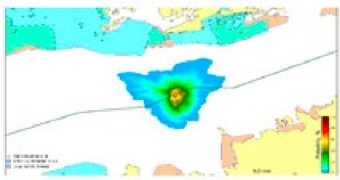
Seatrack Web: A tool for environmental risk assessment in the Baltic

Input data:
- wreck-specific area - model domain
- position of the wreck
- oil type
- direction and data on sea currents
- direction and velocity of wind
- duration of modelling (time window)
- other complementary data (if available): suspended sediment; settling velocity; oxygen content; temperature profile; salinity profile

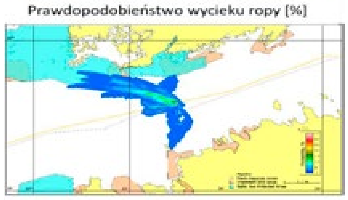
Modelling output maps



Dryf wycieku ropy 23.07.2007



Prawdopodobieństwo wycieku ropy [%]



Prawdopodobieństwo dryfu wycieku [%]

A

A

Quantification of risk for sensitive areas and selected environmental receptors

Ecological sensitive marine receptors:
- coastal and marine protected areas (to protect biological resources),
- marine mammals (cetaceans, porpoises, seals),
- birds,
- fish (nursery and spawning grounds),
- benthos communities

Socio-economic sensitive marine receptors:
- infrastructure at sea (wind farms, mining installations, water intakes for industry e.g. nuclear power plants, aquaculture, ports etc.)
- tourism in recreational areas along the shore, diving, kitesurfing
- demersal, pelagic fishery and crustaceans,
- shipping,
- others – e.g. protected wrecks

Marine living organisms	Low risk	Medium risk	High risk
Living organisms	< 0,2	0,2-1,0	> 1,0
Birds	< 0,002	0,002-0,2	> 0,2

Risk assessment criteria	Relevant oil spill model (shoreline, sea surface, water column or sediment)	Low (score as 1)	Medium (score as 2)	High (score as 3)
Coastal and marine protected areas	water column, sediment, sea surface and shoreline	< 0,002	0,002-0,2	> 0,2
Species and features of conservation interest				
Marine mammals (seals)	water column, sea surface and shoreline	< 0,2	0,2-1	>1
Marine mammals (cetaceans and sirenians)	water column and sea surface	< 0,2	0,2-1	>1
Marine Reptiles	water column, sea surface and shoreline	<0,2	0,2-1	>1
Seabirds	sea surface and shoreline	<0,002	0,002-0,2	>0,2
Benthic features and species including designated shellfish grounds	water column and sediment	Predicted total footprint of oil deposition on sediment <100 km^2 and <0.002 PEC/PNEC risk of any overlap with protected benthic features and species.	Predicted total footprint of oil deposition on sediment between 100-1 000 km^2 or 0.002-0.2 PEC/PNEC risk of any overlap with protected benthic features and species.	Predicted total footprint of oil deposition on sediment >1 000 km^2 or >0.2 PEC/PNEC risk of any overlap with protected benthic features and species.
Fish spawning and nursery areas	water column and sediment	No known spawning or nursery areas.	Oil spill interacts with known discrete areas used for spawning and/or nursery area.	Oil spill interacts with high intensity spawning and/or nursery areas.
Fish (sensitive or charismatic species)	water column and sediment	No known species.	Oil spill interacts with known discrete areas used by sensitive or charismatic species.	Oil spill interacts with area used by large numbers of sensitive or charismatic species.
Shipping				
Important shipping lanes	Sea surface	No overlap with any important shipping lanes.	Seasonal overlap at a concentration above the threshold with any important shipping lanes.	Year round overlap at a concentration above the threshold with any important shipping lanes.
Ports	Shoreline	No overlap with any ports.	Seasonal overlap at a concentration above the threshold with any ports.	Year round overlap at a concentration above the threshold with any ports.

For acute releases the area covered with oil with relations to the site specific area	
Low risk	< 5%
Medium risk	5-50%
High risk	> 50%

B

B

Risk assessment criteria	Relevant oil spill model (shoreline, sea surface, water column or sediment)	**Low** (score as 1)	**Medium** (score as 2)	**High** (score as 3)
Current and planned infrastructure				
Offshore wind farms	Sea surface	No overlap of sea surface oil with any windfarm.	Seasonal overlap of sea surface oil at a concentration above the threshold for more than 5% of a windfarm lease area.	Year round overlap of sea surface oil at a concentration above the threshold for more than 5% of a windfarm lease area.
Offshore oil and gas installations	Sea surface	No overlap of sea surface oil with any installation.	Seasonal overlap of sea surface oil at a concentration above the threshold for any installation.	Year round overlap of sea surface oil at a concentration above the threshold for any installation.
Industrial water intakes	Shoreline	No overlap with any industrial water intake.	Seasonal overlap at a concentration above the threshold with any industrial water intake.	Year round overlap at a concentration above the threshold with any industrial water intake.
Aquaculture	Water column and sea surface	No overlap with any aquaculture facility.	Seasonal overlap at a concentration above the threshold with any aquaculture facility.	Year round overlap at a concentration above the threshold with any aquaculture facility.
Tourism and leisure areas				
Tourism	Shoreline	No overlap with any known tourist areas impacted.	Seasonal overlap at a concentration above the threshold of any known tourist areas impacted.	Year round overlap at a concentration above the threshold of any known tourist areas impacted.
High use areas	Shoreline	No overlap with any high use areas.	Seasonal overlap at a concentration above the threshold with any high use areas.	Year round overlap at a concentration above the threshold with any high use areas.
Fishing grounds				
Demersal	Sediment and sea surface	<180 days of fishing effort impacted in area of oil contamination occurring.	180-365 days of fishing effort impacted in area of oil contamination occurring.	>365 days of fishing effort impacted in area of oil contamination occurring.
Pelagic	Water column and sea surface	<180 days of fishing effort impacted in area of oil contamination occurring.	180-365 days of fishing effort impacted in area of oil contamination occurring.	>365 days of fishing effort impacted in area of oil contamination occurring.
Crustacean	Sediment and sea surface	<180 days of fishing effort impacted in area of oil contamination occurring.	180-365 days of fishing effort impacted in area of oil contamination occurring.	>365 days of fishing effort impacted in area of oil contamination occurring.

For acute releases the area covered with oil with relations to the site specific area	
Low risk	**< 5%**
Medium risk	**5-50%**
High risk	**> 50%**

C

C

Final risk score

Final ecological risk assessment score =
likelihood of release × ecological risk

Final socio-economic risk assessment score =
likelihood of release × socio-economic risk

Final ecological risk assessment score	
Score min = 90	Low risk <240
	Medium risk 240-360
Score max = 810	High risk >360

Final socio-economic risk assessment score	
Score min = 60	Low risk <160
	Medium risk 160-240
Score max = 540	High risk >240

Calculating confidence score

High confidence >80%	Medium confidence 50 – 80%	Low confidence<50%

CRITERIA FOR THE OVERALL ASSESSMENT OF RISK

High risk	**Medium risk**	**Low risk**
There is a high potential for oil to be released. Detailed analysis is required to understand the severity of the threat to sensitive marine receptors.	The risk of oil being released is moderate. Further analysis is recommended to understand the severity of the threat to sensitive marine receptors.	The risk of oil being released is minimal. If the condition of a wreck changes a re-assessment is recommended to confirm risk.
RECOMMENDED ACTIONS		
Assessment has shown that there is a considerable threat to sensitive marine receptors, essential management actions will need to be considered.	The assessment has shown there is a threat to sensitive marine receptors, monitoring and that management may be required.	If the condition of a wreck changes a re-assessment is recommended to confirm risk. Monitoring may be required.

DEFINITIONS OF CONFIDENCE LEVELS IN THE RISK ASSESSMENT PROCESS

High confidence	**Medium confidence**	**Low confidence**
The data and information used are timely, the best available, robust and the outputs are well supported by evidence. There is consensus amongst experts.	The data and information is based on limited evidence and or proxy information. There is a majority agreement between experts; but conflicting evidence/opposing views exist.	The data and information is limited and is not well supported by evidence. There is no clear agreement amongst experts.

FINAL RISK ASSESSMENT REPORT

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CHAPTER 4: METHODOLOGY FOR CONDUCTING GEOPHYSICAL SURVEYS

Conducting any research or measurements on a wreck or in its immediate vicinity requires precise positioning of both the research unit and the measuring tools. Satellite GPS positioning systems are an essential element of a precise positioning. Due to the need for the highest possible accuracy, GPS systems work in the RTK GPS (Real Time Kinematic) system. At present, the position defined by the satellite systems is the basis for positioning of all measuring tools installed on a vessel, as well as towed or water-based equipment. Many systems require additional stabilisation, e.g. multi-beam sonars, therefore, high accuracy devices are used to determine instantaneous values of deviation of the measuring device from the reference plane in all directions. This significantly increase the accuracy of identifying the objects' position. These devices use the laser light and inertial systems, e.g. Hydrins or WaveMaster. Acoustic positioning systems are used for locating objects in the water (towed sonar, ROV and autonomous vehicles). Systems with ultra-short base (USBL) are the most commonly used.

Deliverables/results are the only tangible decision-making tool within a specific project on a given wreck. Therefore, before designing any research process or developing a methodology, the data, information and deliverables required to answer the project's questions should be defined. Only then can the most effective equipment be selected and the most appropriate method of operation can be determined. The measuring devices currently in use are listed below. In the future, these instruments will certainly have better parameters, and thus the measurement results will be more accurate.

4.1 Positioning systems

4.1.1 RTK GPS – Trimble SPS 851 satellite positioning system

The RTK GPS satellite positioning system Trimble SPS 851 (Figure 5) is used to position the measurement sensors within the parameters correction area RTCM RTK. It uses the position correction sent from EUPOS/SAPOS systems via an internet connection. The positioning system is linked to the measurement sensors through the software of the integrated QINSy navigation system. The system is also used in the process of calibrating measurement systems.

4.1.2 System for providing the heeling lever, heading and acceleration

POS MV™ WaveMaster ensures positioning even in very unfavourable weather conditions. Due to the high frequency of measurements, the system allows full measurement of the position and orientation of the measurement unit within the scope of the following parameters:

- position (longitude, latitude and altitude),
- velocity (lateral and vertical),
- heeling lever (longitudinal and transverse) and heading,
- heave,
- acceleration,
- angular rate of turn.

POS MV™ WaveMaster system provides a consolidated solution for measurement vessels, especially in places where the GPS signal is of poor quality. The GPS signal from one or more GPS receivers is used to calculate the position and motion of the vessel (Figure 6).

Figure 5. Trimble SPS 851 satellite system receiver and antenna
(Source: technical documentation)

Figure 6. Inertial positioning system with ship motion sensor Applanix POS-MV (Source: technical documentation)

4.1.3 USBL Sonardyne Ranger 2 underwater positioning system

Sonardyne underwater positioning system allows to determine the position of the tracked object in relation to any point of the measurement unit. In addition to the visualization of the analysed object, it also allows to determine its position digitally and send it to the QINSy system for integration with other parts of the measurement system. The Ranger 2 system (Figure 7) uses the USBL (Ultra-Short Baseline) acoustic positioning method. The heart of the USBL system is a transceiver with acoustic transducers, allowing the measurement of phase shifts of the received acoustic signals.

4.2 Bathymetric and 3D data

Bathymetric data (or depth data) can be acquired using a variety of tools: from a lead line (a calibrated rope and weight) to interferometric airborne laser surveys carried out from an aircraft. The standard way of acquiring bathymetric data is with a multibeam echosounders. Multibeam echosounders are acoustic systems that measure distance through the water column either to the seabed or to underwater structures. Measuring to distance to the seabed allows to determine the water depth. Multibeam echosounders also provide seismic data; the length of the seismic waves depends on the depth of the water. Multibeam echosounders measure a swath of seabed. The length of swath is dependent on water depth. The range and resolution of the system is dependent on the frequency of transmission, the physical properties of the transducers and the processing power of the system.

Figure 7. USBL Sonardyne Ranger 2
(Source: technical documentation)

Multibeam systems operate at a range of frequencies from 150 kHz to 600 Khz. For high resolution surveys, frequencies in the range of 400 kHz are optimal, as at these frequencies data density can be optimized for ranges of less than 100 m. System specifications, resolution and accuracy of measurements, performed by a multi-beam sonar are as follows:

- depth resolution: not less than ±6 mm;
- number of beams: from 256 to 1024 – typical number is 512;
- beam angles: 1 degree versus 0.5 degree systems.

Typically, the multibeam echosounder is interfaced to a positioning system, such as e.g. GPS, and motion reference sensors. As a result, the movement of the survey platform, whether it is a boat or a remotely operated vehicle (ROV), is possible. These systems are combined into an Integrated Navigation System (INS), which collects all the data to determine the position of the object, and also uses a position prediction algorithm to obtain a more accurate location measurement than the sum of the errors of the individual sensors. The INS is interfaced with a data acquisition software in which positional data is combined with multi-beam measurements to determine the x, y, z for each depth measurement within the swath, which is then then stored and processed. The precision of the INS and the multisystem combined, give an accuracy of each data point.

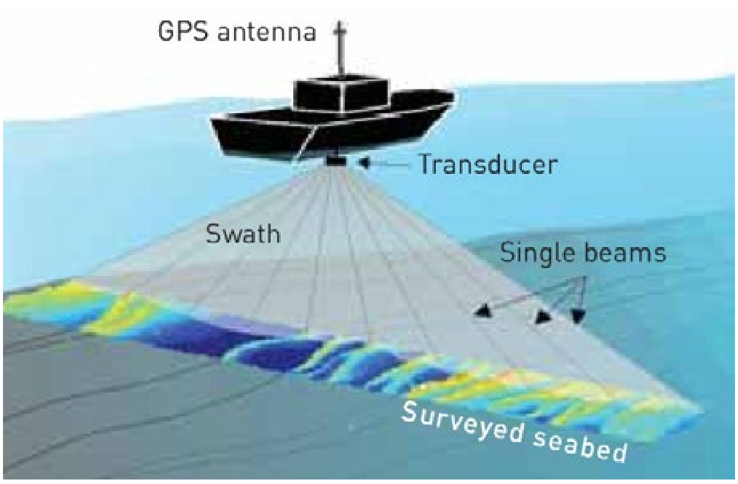

Figure 8. Diagram showing how a multibeam sonar operates (Source: https://www.researchgate.net/figure/Diagram--showing-how-a-multibeam-echosounder-sonar-would-operate--from-a-scientific_fig2_254914411)

4.2.1 Data acquisition methods

Multibeam echosounders allow a high density of measurement points over the target area. Point density depends on the specifications of the multibeam (frequency, beam angle), system range and data acquisition speed. The image below (Figure 9) shows the multibeam bathymetry survey of the War Mehtar shipwreck located off the East coast of the UK.

The point density over the wreck, shown in grey, is approximately every 5 cm. The point density over the seabed area, shown in various colours, is approximately every 10 cm. This survey represents data of the highest quality and utilized the best equipment available on the market. The systems where mounted on a powerful work class ROV, which enabled the survey to be conducted at close range, no more than 10 m from the wreck, and at very slow speed, approximately 0.5 m/s.

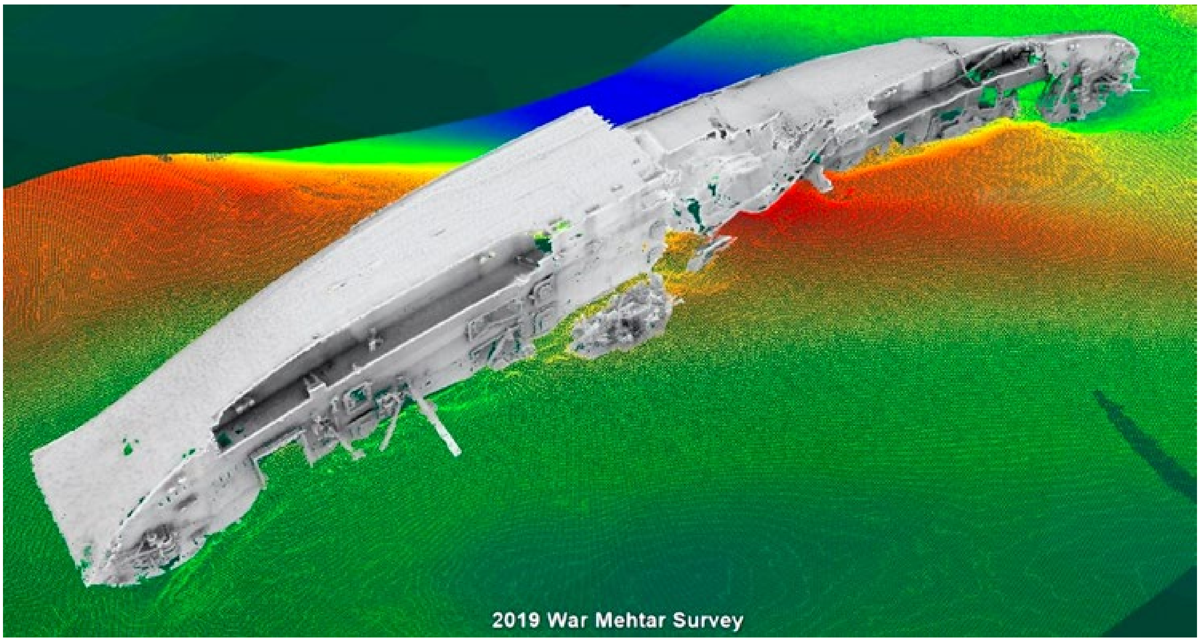

Figure 9. Image of the Methar wreck acquired using the multibeam bathymetry survey
(Source: https://www.waves-group.co.uk/waves-groups-high-resolution-3d-data-acquisition-capability-used-in-legacy-wreck-risk-assessment/)

4.2.2 Data presentation and processing

Multibeam bathymetry systems produce point cloud data. This can be defined as a data file, where each data point is attributed an x,y,z coordinate value. For bathymetric charting it is traditional that the point cloud is then interpolated into a digital terrain model (DTM). This can be done using various algorithms. The advantage of this for charting purposes is that it produces a surface that can be shifted, moved and interrogated with no gaps. The file size and formats of DTMs vary, but they provide a solution for dealing with wide areas of seabed and sparse data densities.

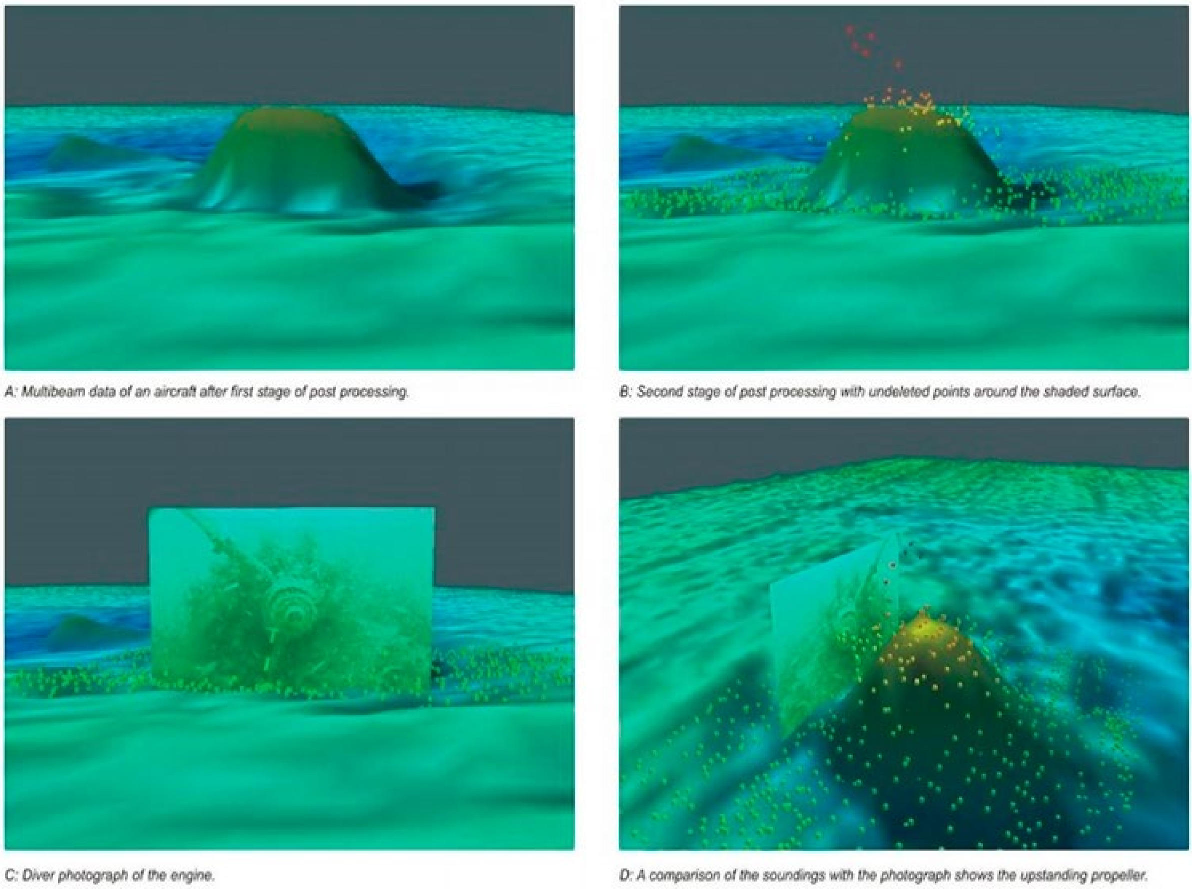

Figure 10. Different techniques – interpreting the results of depth measurements using a multibeam sonar and photography (Source: Wessex Archaeology Ltd)

The alternative is to work with the point cloud. The advantage of which is that detail can be seen or inferred as the points have not been interpolated or smoothed/filtered. The images above (Figure 10) demonstrate the difference between the outputs and data interpretation from a point cloud and a DTM. Image A shows a mound in the DTM and image B shows the original point that have been interpolated to create the DTM. Note the red points in the top of the image B that have been rejected as part of the DTM process. Image C shows a photograph of an aircraft engine, which has been interpolated and shown as a mound. And image D shows that the rejected red points of image B are in fact points on the propeller attached to the engine.

In conclusion, the multibeam sonar has several applications. It can be used to acquire area bathymetric data that is essential for understanding the overall context of the wreck's surroundings and can be used as base data for serval modelling applications. The sonar can also be used to undertake detailed structural survey of the wreck.

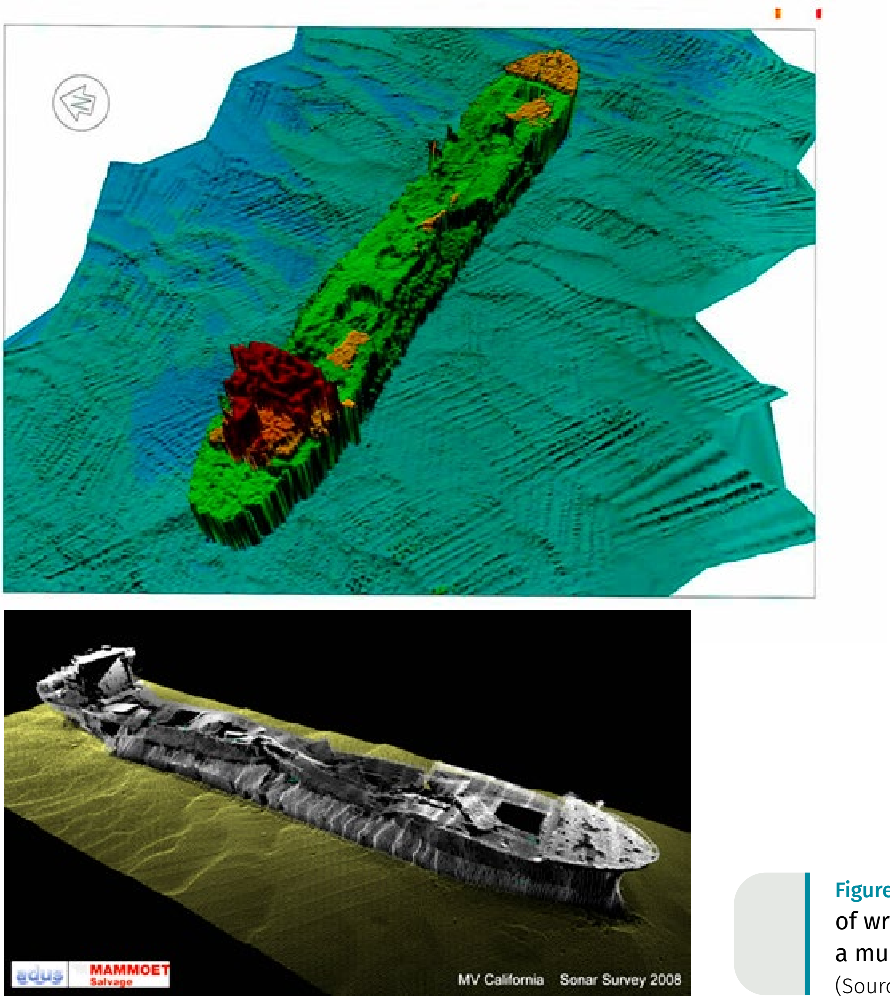

Figure 11. Sample images of wrecks taken with a multi-beam sonar (Source: Waves Group Ltd)

4.3 Sidescan sonar

Side-sonars are acoustic devices that produce an acoustic image of the seabed. The system comprises of a towfish and top side processing unit. Towfish of the side-sonar is equipped with two acoustic transceivers mounted on either side to produce data perpendicular to the direction of travel. The towfish is usually towed at the depth equal to approximately 10 to 20% of the total depth. It is not uncommon for the towfish to be towed higher in the water column, to prevent entanglement in seabed debris. The position of the towfish is derived either in real time with an Ultra Short Base Line acoustic positioning system (USBL); or by calculating the real position of the towfish based on the depth of towing and length of the cable used to hold the sonar from the survey vessel. Digital data from the side-sonar is recorded in the top side processing unit. Systems work on frequencies from 200 to 900 kHz. Low frequencies give longer ranges, but with less resolution imagery.

The sidescan sonar image provides quantitative data but is qualitive in nature. This makes the sidescan sonar a superb tool for characterising the seabed sediments and identifying objects on the seabed, including shipwrecks. The sidescan sonar is used as a wide area search tool. The lower the speed of the sonar towfish, the better the longitudinal resolution and the more valuable information about the shipwreck.

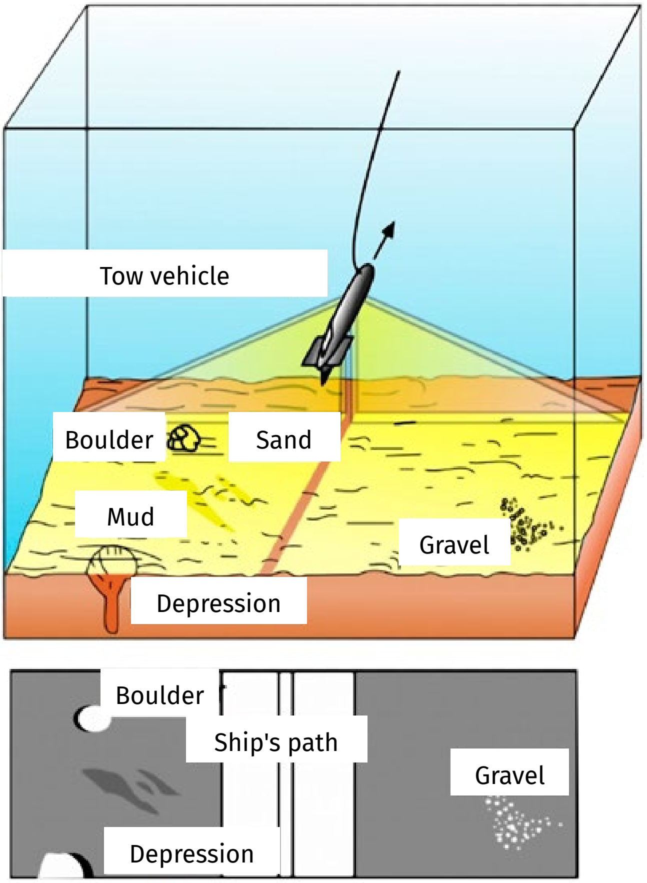

Figure 12. Principle of operation of side-scan sonars (Source: U.S. Geological Survey Department of the Interior/USGS)

4.3.1 An example of a sidescan sonar used in marine surveys

Sonar parameters	EdgeTech 4200:
Frequency of acoustic signal:	Standard resolution: 300 kHz High resolution: 600 kHz
Pulse length:	300 kHz – do 20 ms 600 kHz – do 10 ms
Vertical beam width:	50°
Horizontal beam width:	300 kHz – 0,54° 600 kHz – 0,3°

Figure 13. EdgeTech 4200 towed side-sonar (Source: technical documentation)

The image below shows a sidescan mosaic of an 1 km × 2 km area of seabed. It can be seen that the general character of the seabed can be described and objects in the order of 10m dimension can be identified.

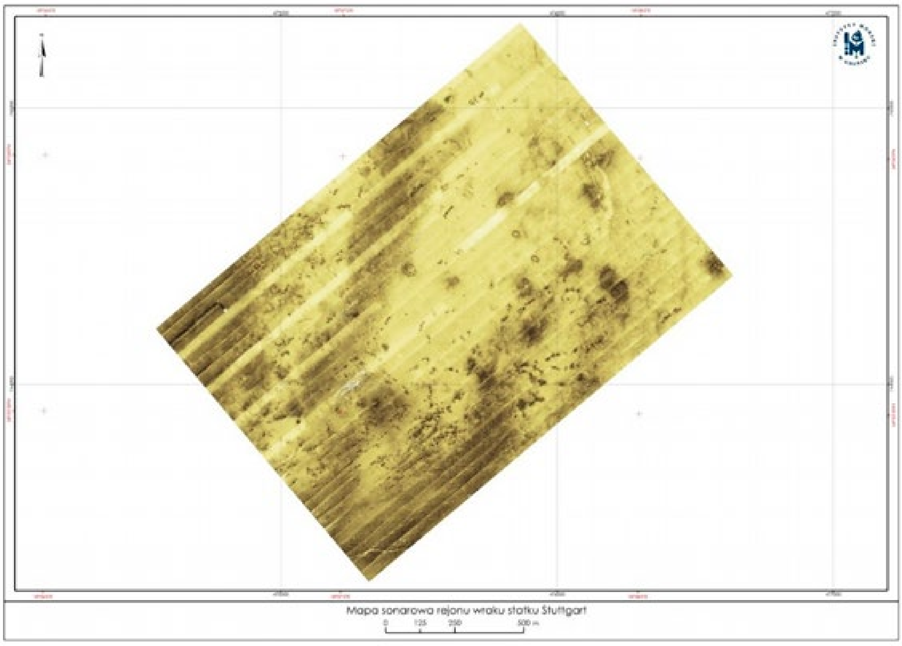

Figure 14. Sonar mosaic of the surveyed site carried out with a sonar with towfish EdgeTech 4200 (Own source)

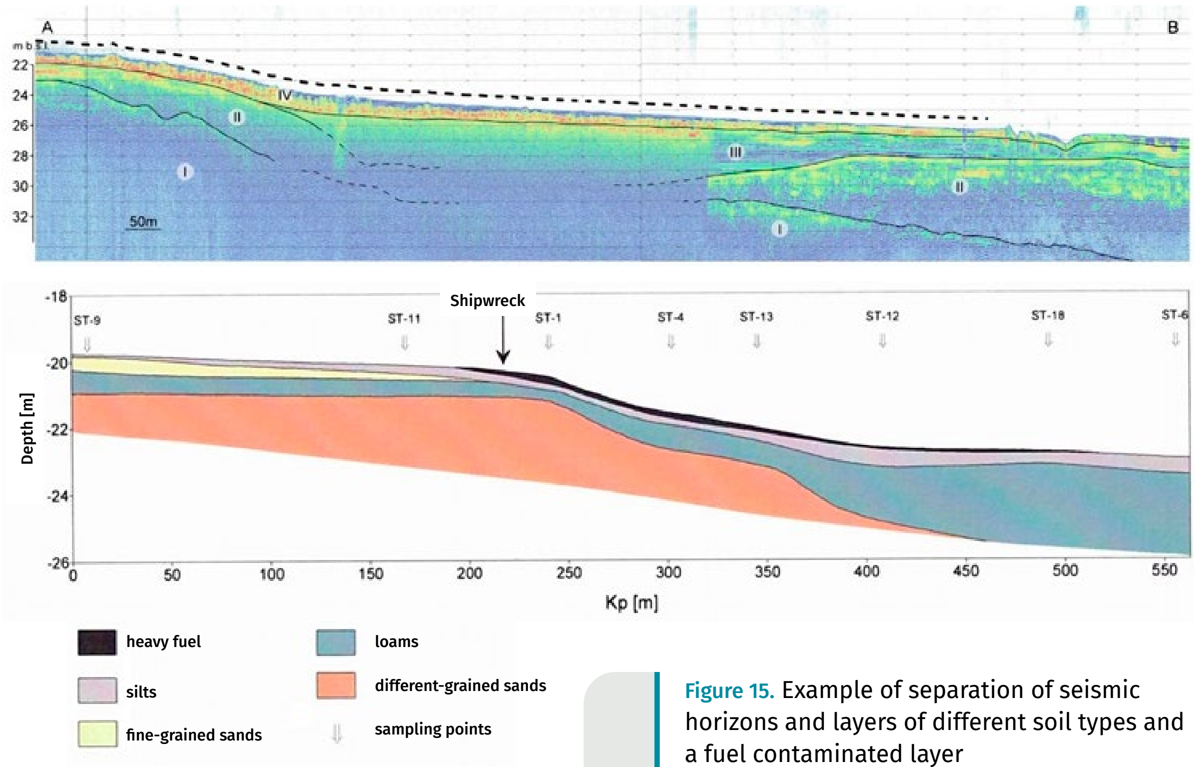

Figure 15. Example of separation of seismic horizons and layers of different soil types and a fuel contaminated layer (own source)

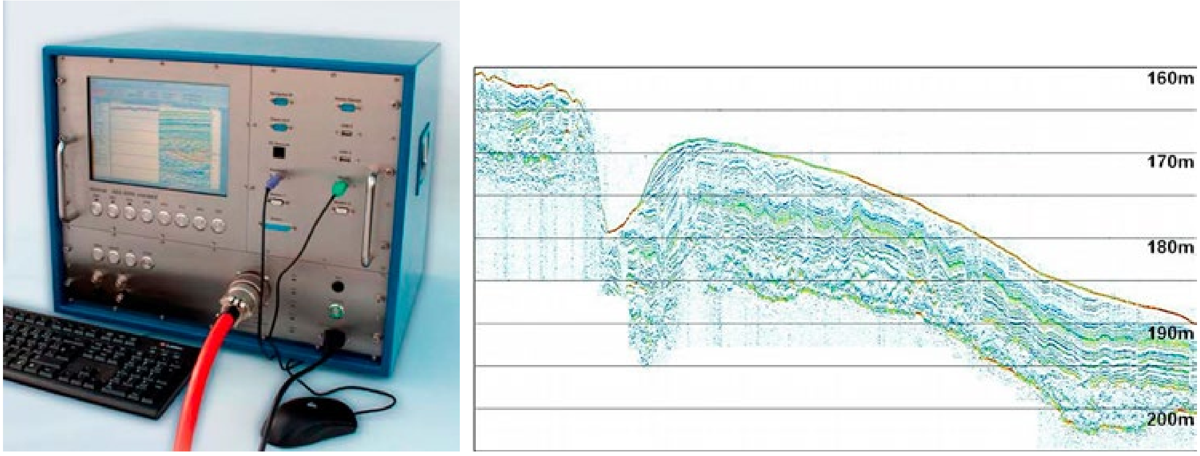

Figure 16. Innomar SES-2000 sub-bottom profiler and an example of its record (Source: technical documentation)

Technical parameters SES-2000:

Frequency of acoustic signal:	85-115 kHz
Pulse length:	0,07-1,0 msec (optional)
Vertical beam width:	±2°
Water depth range:	300 m
Penetration:	to 40 m (depending on the sediment grain size)
Resolution:	1-5 cm

4.4 Sub-bottom profilers (SBP)

A shallow seismic survey with the use of acoustic profilers is performed to find objects that were once part of the shipwreck or its cargo, and are currently covered with a layer of bottom sediments brought by sea currents. Quite often, during such a survey it is possible to detect another feature of the seabed, which is a layer of sediments soaked with heavy fuel from the shipwreck. An example of such a discovery is shown in the Figure 15. The survey was conducted near the S/S Stuttgart shipwreck, from which approximately 600 to 800 tonnes of fuel had leaked. When a sediment layer contains a large amount of heavy fuel, due to its capacity to absorb a low frequency sound penetrating the seabed, everything underneath such a layer is no longer visible on the sonogram. The attached example shows what should be looked at. As a result of the performed interpretation, the type and thickness of sediments were determined, as well as subsurface geology, and on the basis of detailed seismic analysis the main seismic units were identified. The basis of identification consisted of variation in the intensity and composition of light reflexes and the nature of unit boundaries. The detailed image of separated units and examples of seismic sections are presented in Figure 15.

High-frequency seismoacoustic profilers, e.g. Innomar SES-2000 Medium profiler, are used for seismoacoustic research of the surface layers of the seabed. The SES-2000 profiler is composed of a unit with a PC to operate the system and a transducer, mounted on the side of a measurement vessel. The system works at two frequencies: high frequency with basic frequencies (approx. 100 kHz) are used for precise determination of depth, and low frequency (4–15 kHz), used for penetration of sediments in the seabed. An acquisition system is used for registering data. It records an electronic version of acoustic deep penetration of the seabed that permits to see the layers of the sediment and whether there are any hard objects, such as the elements of the wreck or cargo.

4.5 Magnetometer Surveys

The main purpose of magnetometer surveys is to detect the presence of ferromagnetic objects in the survey area. Data containing magnetic induction parameters registered by the magnetometer are difficult to interpret, mainly due to their time and location dependence. In addition, the magnetic field strength at every point in space is the vector sum of the value of the natural earth magnetic field and in the case of the presence of an object with ferromagnetic parameters in the measurement area, its magnetic dipole moment. The signal registered by the magnetometer also includes: the noise interfering with the correct signal, which can be generated by the electric device (magnetometer, rope and ship); daily variations of the Earth's magnetic field caused by the sun; noises of the measuring device; communication errors between the measuring device and the recording system, as well as the noise generated by sea waves. In order to reduce this type of interference, signal filtering should be used to eliminate all high frequency components.

The size of the magnetic anomaly depends, among others, on the mass of such object and is approximately inversely proportional to the cube of the distance of a measuring device from the target when recording the signal. This means that the size of the searched ferromagnetic object determines the distance from the magnetometer to the object at the seabed. The main parameters which affect this distance are: the height above the seabed at which the device is moving during the measurement, the burial depth of the object and the distance between measurement profiles. Examples of registered changes in the magnetic field along the measurement profile are presented in the Figures 17 and 18.

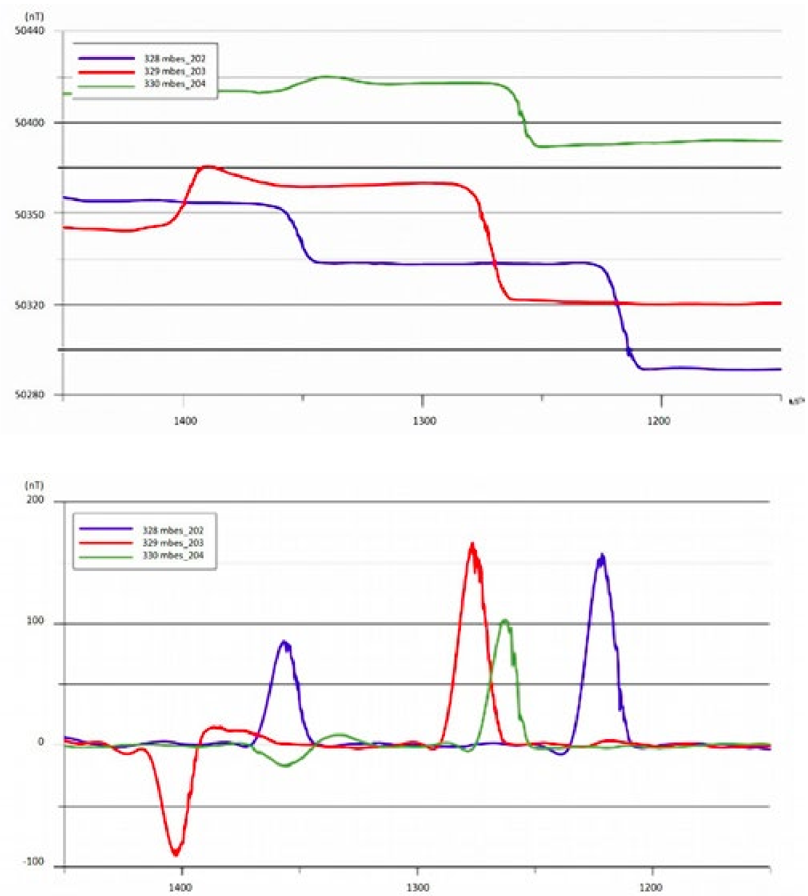

Figure 17. Examples of magnetic field strength graphs registered on 3 measurement profiles, recorded on a measurement site during previous works and graphs of data from the same profiles after filtration (Source: own source)

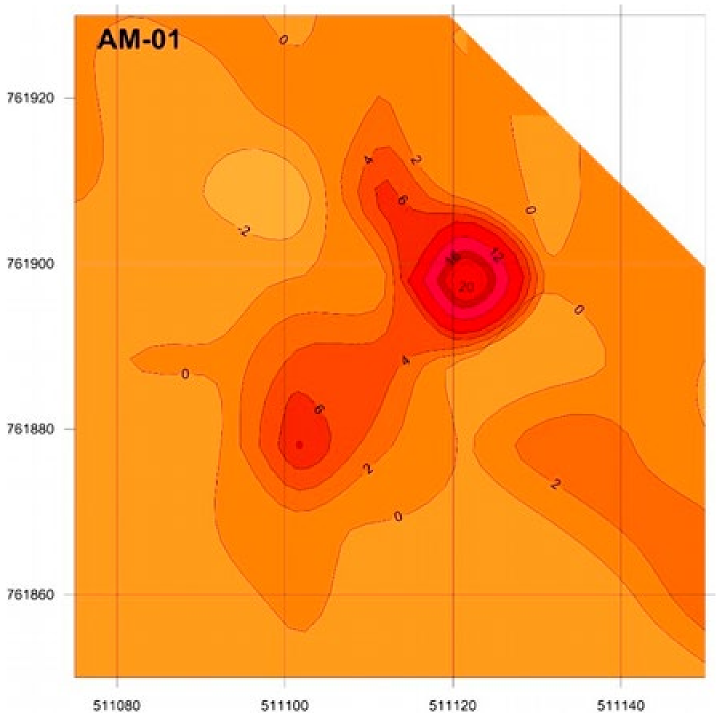

Figure 18. Enlarged fragment of the map of magnetic anomalies, with the anomaly of the Muhlhausen shipwreck visible in detail (own source)

The most effective method of carrying out a measurement, with which it is possible to detect the largest number of objects, is to place the measurement profiles densely and keep the magnetometer as close to the bottom as possible. However, such conditions may not always be met. The nature and natural conditions of the studied area are the main factors that determine the method of conducting research. If the measuring device is placed too low in variable bathymetry or varied bottom morphology, the device may hit the bottom or be towed. Too low guidance of the measuring device with a variable bathymetry or different shape of the bottom, there is a risk of hitting or dragging the device on the ground. In the case of measurements on objects towering above the bottom (e.g. metal wrecks), the height of the magnetometer is even more important, because the impact of the sensor on the object may not only damage it, but also cause its loss. The magnetometer may catch on protruding elements or become entangled in the net on the wreck. This often causes the cable to break and as a result the sensor gets lost.

The dense distribution of measurement profiles increases the time and costs of the survey. In order to choose the most optimal measurement method, it is necessary to determine the smallest expected mass of objects deposited on the bottom, which are to be localised, under the assumption that the minimum anomaly value indicating the presence of a ferromagnetic object in the survey area is 5 nT. It is also necessary to take into account the fact that smaller objects can be detected only at a certain height or in a small distance from a given measurement profile, whereas only large weight objects can be detected in the space between the profiles. If measurement profiles are located at a distance of 30 m and the magnetometer operates at a height of 6 meters above the seabed, an object weighing 0.5 tonnes lying in-between the profiles will create an anomaly of 1,2 nT, whereas the same object located on the measurement profile will create an anomaly of

Table 7. **Minimal distance of a ferromagnetic object from a measurement device, assuming the detection of 5nT** (on the basis of Hall's equation Hall'a 1966)

Distance (m)	Mass of the object (kg)
5	63
6	108
7	172
8	256
9	365
10	500
12	864
14	1372
16	2048
18	2916
20	4000

24 nT (Hall 1966). Typical values of object detection (for an anomaly equalled 5nT) are presented in the Table 7. Based on the collected data on magnetic anomalies in a specific area, it is very useful to perform a spatial distribution of the anomalies as shown in Figure 19.

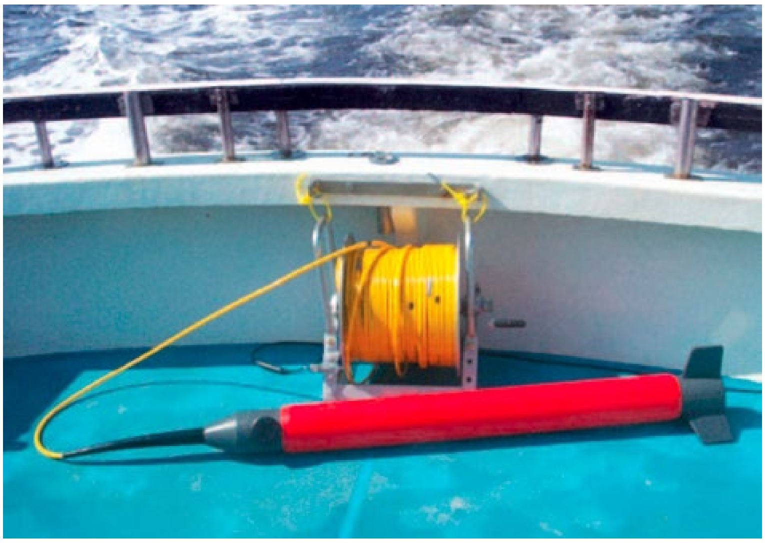

Figure 19. SeaSpy proton magnetometer (own source)

Figure 20. Gradiometer (differentia magnetometer) composed of two incorporated SeaSpy proton magnetometers (Source: technical documentation)

A proton magnetometer is usually used to measure magnetic anomalies in projects related to wreck search and research, using the Overhauser effect. The Figures 19 and 20 show a device produced by a Canadian company Marine Magnetics. It is characterized by a very high resolution (0.001 nT) and absolute accuracy (0,2 nT).

In the case of the S/S Stuttgart wreck (Figures 21 and 22), a proton magnetometer SeaSpy was used to identify the magnetic induction field of the wreck and other metal objects scattered around the wreck. Figures 20 and 21 show a rather non-standard induction isoline system in the form of a multiple dipole. A single dipole is very characteristic of a large mass of a ferromagnetic, constituting a homogeneous magnetic mass. The combination of several dipoles visible on this picture suggests that there are several, separate magnetic objects at the seabed, placed far enough from each other to distinguish them. This may indicate that the wreck is entirely built of steel. The starboard is still buried in the bottom sediment, but on top of it there are several large objects made of steel or other ferromagnetic materials, such as boilers (or their parts) and propulsion units, or rather what is left of them. The intensity of the magnetic field around the wreck varies in the range of 300 nT/30m to 450 nT/30m.

Considering that these are values measured with a gradiometer, it can be assumed that there are still several hundred tonnes of steel and other ferromagnetic materials at the sea bottom. On the basis of the data from previous measurements it is possible to estimate an approximate weight of these objects

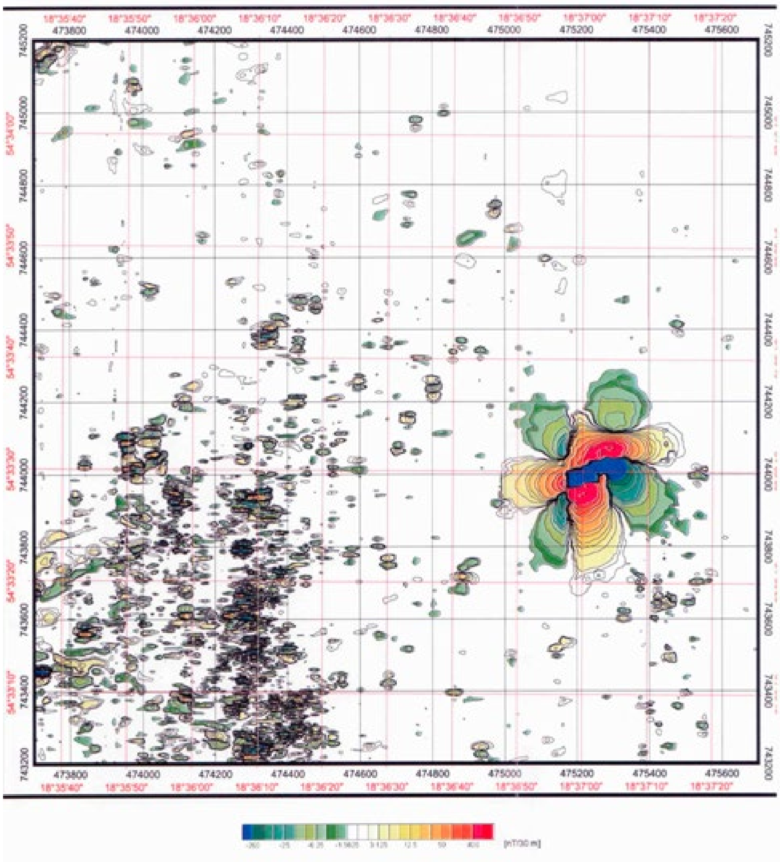

Figure 21. Isolines created by the anomaly of the magnetic induction field, caused by the magnetic field around the S/S Stuttgart wreck and other objects lying in the vicinity (own source)

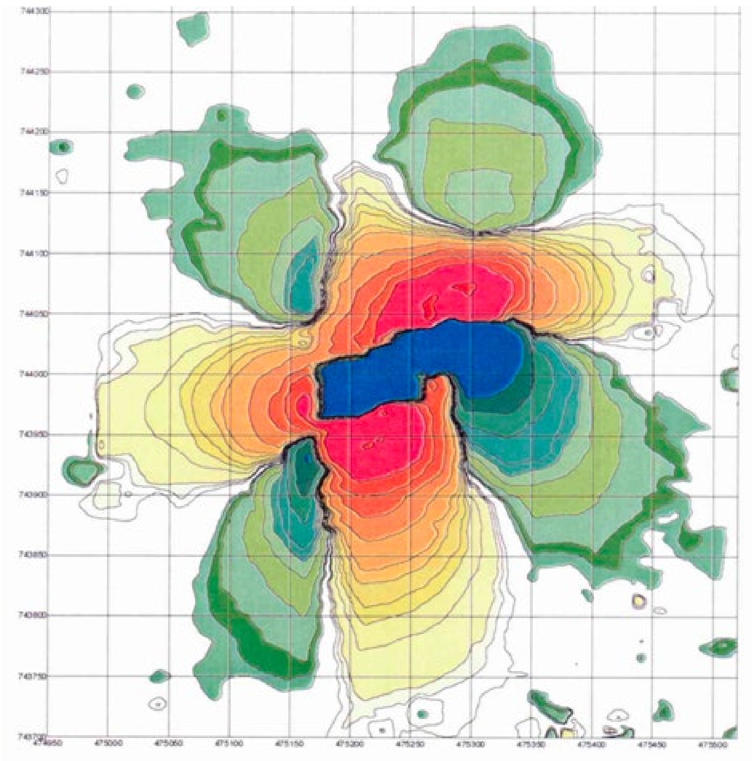

Figure 22. Isolines created by the anomaly of the magnetic induction field, caused by the magnetic field around the S/S Stuttgart shipwreck - the area limited to the wreck itself (own source)

4.6 Marine laser systems

In certain cases, it is possible to use laser systems for sea-bed mapping. They are not easily accessible due to the costs and limited use. These systems are mounted on towed vehicles, remotely operated vehicles (ROV) or autonomous underwater vehicles (AUV).

Accurate positioning of a remotely operated, towed vehicle is ensured by the differential GPS positioning system connected with acoustic positioning devices (USBL) in deep waters. They are often integrated with the inertial navigation system, mounted on the same platform. The data generated by sensors are transmitted by a high-capacity telemetry link to the measuring vessel and processed with an integrated measurement system. The SAIC system is an example

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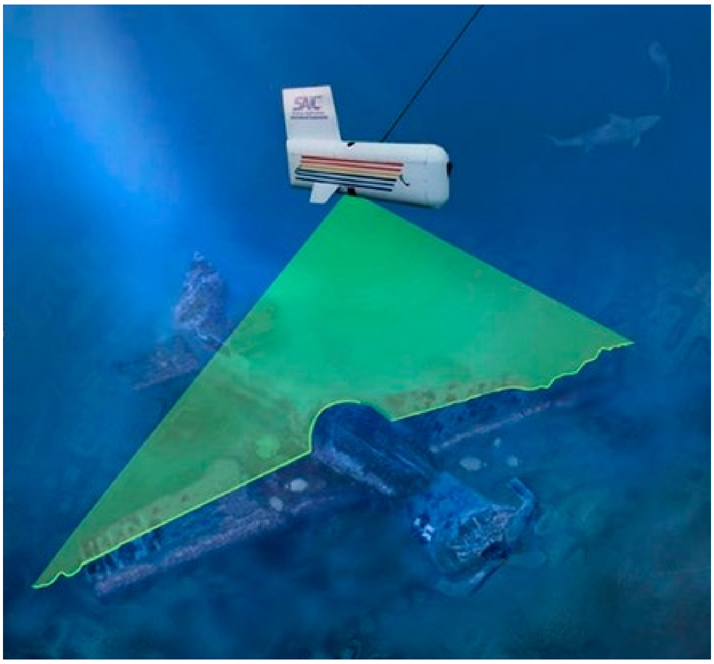

Figure 23. SAIC towed vehicle (Source: www.saic.com/llss/#general)

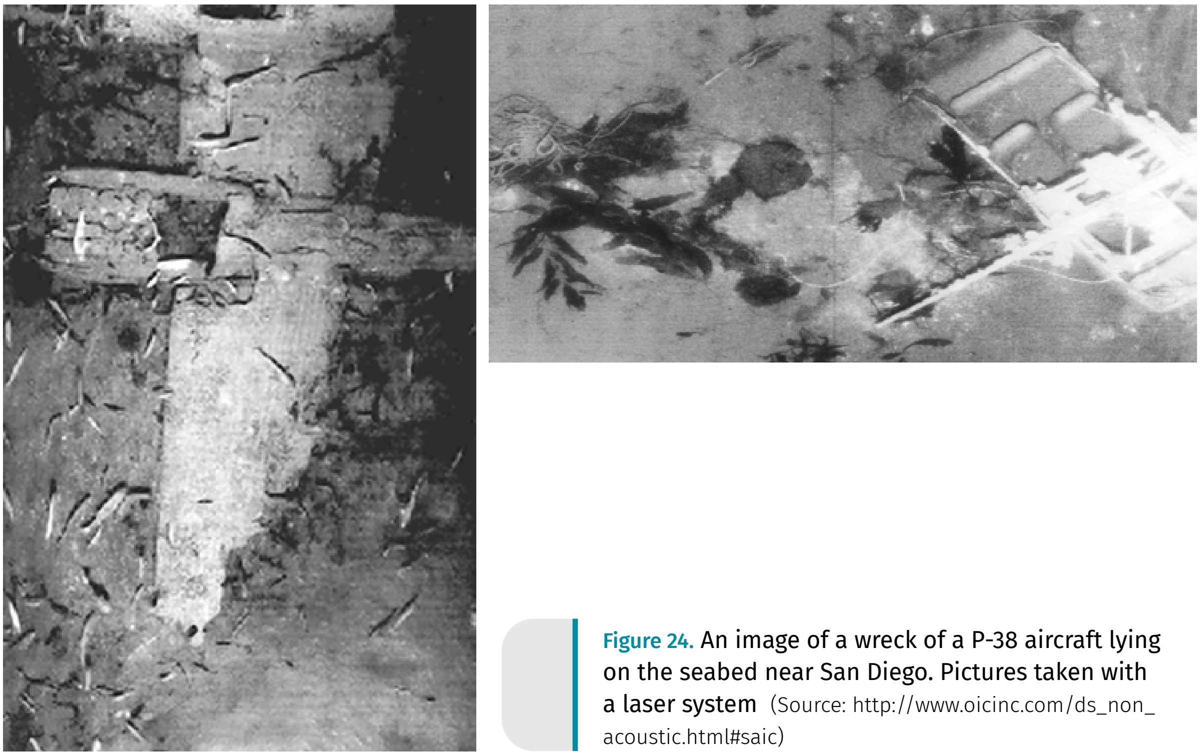

Figure 24. An image of a wreck of a P-38 aircraft lying on the seabed near San Diego. Pictures taken with a laser system (Source: http://www.oicinc.com/ds_non_acoustic.html#saic)

4.7 Systems supporting environmental data collection

4.7.1 Sensors used for measurements of temperature, salinity, and oxygen content

Mini CTD Valeport sensor (Figure 25A) is used to measure electrolytic conductivity and temperature. It registers the electrolytic conductivity in the range of 0 to 80 mS/cm, with a 0.001 mS/cm resolution and temperature in the range of -5 to 35°C, with 0.001°C resolution.

A)

B)

Figure 25. Examples of sensors used for measurements of temperature, salinity and oxygen content in the water: A) mini CTD Valeport sensor, B) mini SD204 SAIV A/S sensor (Source: technical documentation)

SAIV SD204 sensor (Figure 25B) is used to measure temperature and electrolytic conductivity, and is equipped with an oxygen measurement device. It registers the conductivity in the range of 0 to 70 mS/cm, with 0.001 mS/cm resolution, temperature in the range of -2 to 40°C with 0.001°C resolution, and dissolved oxygen in the range of 0-20 mg/l, with 0.01 mg/l resolution.

4.7.2 AWAC profiler for measurements of currents and waves

AWAC doppler profiler is used to measure currents and waves (Figure 26). After programming, the AWAC measuring profiler is placed on the seabed, where it conducts automatic registration until it is taken out and placed on board a vessel.

Figure 26. AWAC Nortek acoustic current profiler (Source: technical documentation)

The device has 4 acoustic sensors to measure sea currents and waves, a pressure sensor for measuring the average sea level and a temperature sensor. The measurement of instantaneous deflections of the waves is carried out at one-hour intervals, for approx. 17 minutes, at a frequency of 2 Hz. Also, the measurement of water flow velocity in the vertical profile is usually carried out at one-hour intervals. The averaging of flows is performed for 2-minute periods, separately for each water layer with a thickness of 4 m.

4.7.3 Environmental monitoring buoy

An important element of environmental studies is the determination of hydrometeorological conditions. There are many possibilities to acquire this data. It can be obtained at the centres of meteorological services (in Poland at the Institute of Meteorology and Water Management) that have an integrated network of sensors for measuring all parameters of wind and pressure, such as their distribution over time etc. It is possible to use mathematical models, if they have sufficient accuracy for the purposes of the project. These models are used to monitor such parameters as: wind, sea currents at different levels and waves. The projects carried out by the Maritime Institute in Gdańsk used a hydrometeorological buoy (Figure 27). It was an integrated hydro-meteorological centre transmitting the following data via radio in real-time:

- air temperature;
- wind direction and speed;
- atmospheric pressure;
- relative air humidity;
- concentration of oxygen dissolved in water;
- water turbidity;
- sea current direction and strength at levels at 4 m intervals from the seabed to the surface.

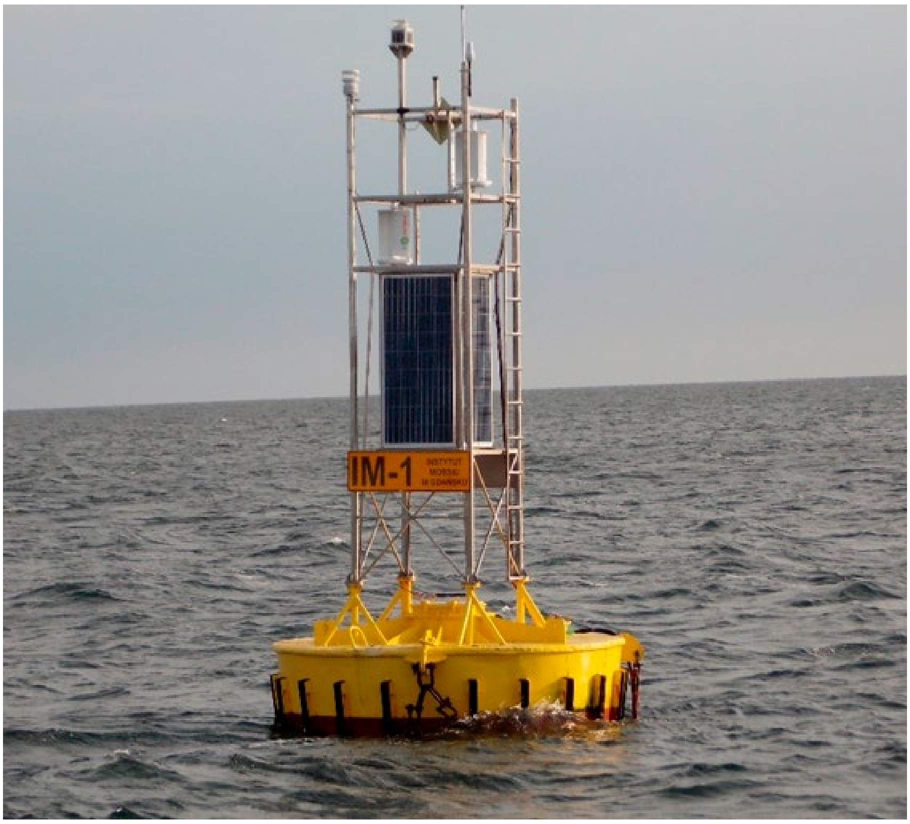

Figure 27. The measuring buoy of the Maritime Institute in Gdańsk
(Source: Maritime Institute in Gdańsk)

4.8 **Geological analysis**

4.8.1 Scoop sampling

Sampling of surface sediments with samplers (e.g. a Van Veen sampler), provides material for chemical, geological and biological analysis. Sampling should take place in places characteristic for the area, where the shipwreck is located. The size of the sampler is also important. If the sample is to be used only for chemical analysis, then it is sufficient to collect approx. 1 kg of mass. If a geological analysis to check the distribution of the grains (which may be important to identify the conditions under which the soil will migrate due to the sea currents) is also to be performed, it will be necessary to take a sample twice as large. In the case additional samples are taken for biological and ecotoxicological analysis, the volume of the sample should amount to at least a dozen or few dozen litres, i.e. approx. 25-40 kg. The material of the sample (after deducting appropriate parts for the above mentioned analysis) will be washed in a scrubber in order to isolate macrobenthos living in the surface layer of the sea bottom.

The samples should be taken with a scoop covered with lids, which prevents the escape of animals living in the soil. When taking samples only for geological and chemical analysis the scoop can be open from above, whereas for biological and chemical analysis it should be protected with a grid as presented in the Figure 28. The choice of the sampling site should be considered in advance and should take into account the current conditions at the bottom. Important parameters for the selection of the sampling sites have been mentioned earlier.

A typical Van Veen sampler is an example of a sampler used for collecting surface sediments. The one shown in the Figure 28 is the sampler weighing 60 kg and of a sampling surface of 0.1 m^2.

Experience shows that 4-6 samples taken around the wreck are completely sufficient to recognise the conditions at the bottom. However, there are cases where more samples are needed. As many as 1 022 samples had to be taken to recognise the entire contaminated zone around the Stuttgart shipwreck. Carrying out chemical analysis of all samples would have been extremely expensive, therefore all samples were described on the basis of organoleptic tests, i.e. performed with the use of senses and sensory analysis (using several senses at the same time), including: the smell, appearance, texture, and other signs indicating the presence of fuel or only a fuel film in the sample. This analyses were carried out immediately after the samples had been taken from the bottom, on board the research vessel.

It is impossible to carry out complete chemical analysis of the seabed on board a vessel and there are no testes allowing for rapid classification of the sediment according to the contamination level. In literature and in practice referring to sediment surveys around shipwrecks (both on global and national level) there is no indication of the methods used to carry out these analyses. It can therefore be assumed that organoleptic method for testing samples proposed in the project is our original solution, which, as demonstrated in practice, is sufficiently accurate to quickly classify the samples contaminated with fuel. The result of organoleptic analysis is subjective and as such can be unreliable. In order to increase the accuracy and correctness of the results, the assessment (classification) of samples during sampling was preceded by a training of the assessment team, carried out by people with proven sensory capacities. As a result of the training, the scale and assessment parameters had been harmonised and therefore one solution, that is a 5-scale classification of sample contamination, was adopted, based on such indicators as: smell, appearance, fuel film on water surface etc.

Samples were divided as follows:

0 – clean

1 – slightly oiled

2 - medium oiled

3 – heavily oiled

4 – very heavily oiled / fuel

Figure 28. Van Veen sampler during work on board R/V IMOR
(Source: Maritime Institute in Gdańsk)

Examples of pictures from oiled samples of bottom sediment are shown in Figures 29.

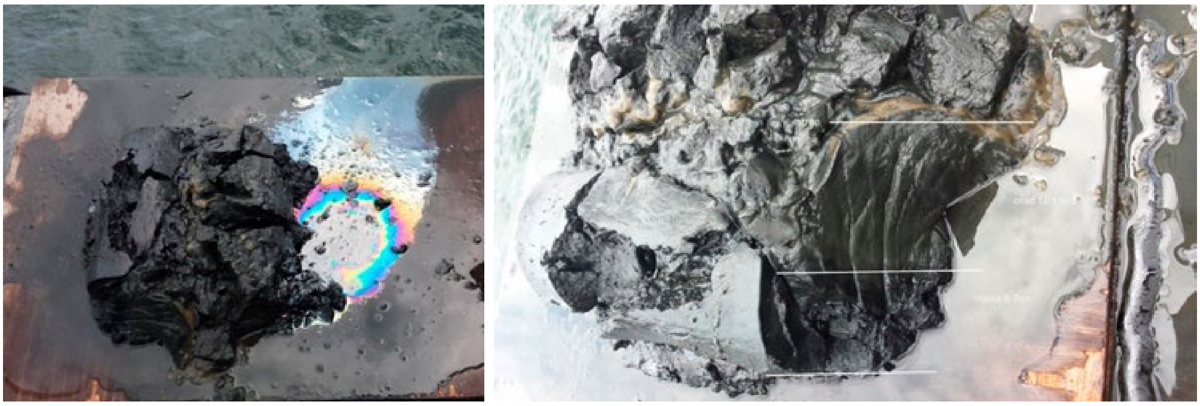

Figure 29. Sediment samples taken with a scoop – on the left an oil film visible on water surface, on the right a layer of heavy fuel of few centimetres (Source: Maritime Institute in Gdańsk)

The assessment of the fuel contamination of different samples was used to determine the spatial distribution of samples with different parameters, and thus to determine the extent and type of contamination of the entire area around the wreck. During sampling, every 5th sample was sent to the laboratory for chemical analysis in order to objectively determine if the sample is contaminated and with what substance. In the case of contamination with petroleum products, it is relatively easy to determine due to due to the intensive, very characteristic smell of hydrocarbon.

4.8.2 Core samples

Usually, short cores are sufficient to determine whether there are layers of contaminated sediments around the wreck. A vibration probe, e.g. VKG-03 type, is used to collect core samples up to 3 m in length (Figure 30). The collected cores undergo a geological and chemical analysis. After macroscopic description, the cores undergo an analysis to determine the metal content (including heavy metals), non-polar aliphatic hydrocarbons, aromatic hydrocarbons and polychlorinated biphenyls.

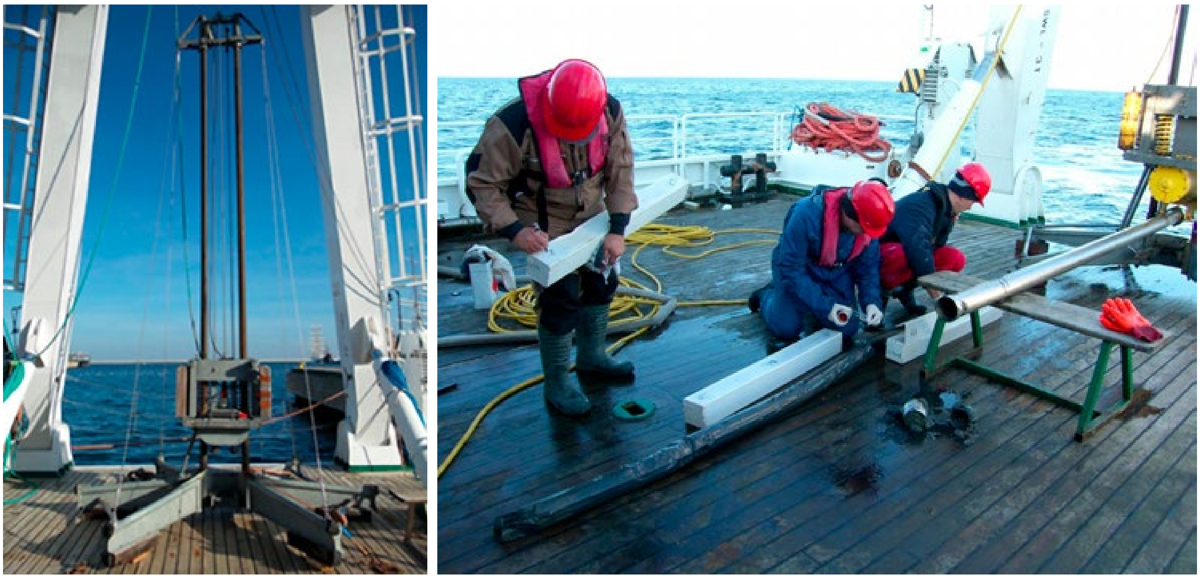

Figure 30. Core sampling with a vibration probe on board IMOR vessel
(Source: Maritime Institute in Gdańsk)

The cores may be taken in a plastic sleeve or a rigid PCV pipe. They are usually divided into sections of not more than 1 m in length, which are described and then transported to the geological laboratory for analysis. After removing the core from a protective box, the plastic sleeve and then the top cover of the core are cut. After cutting and cleaning, the surface of the core is prepared to take a documentary photo (Figure 31).

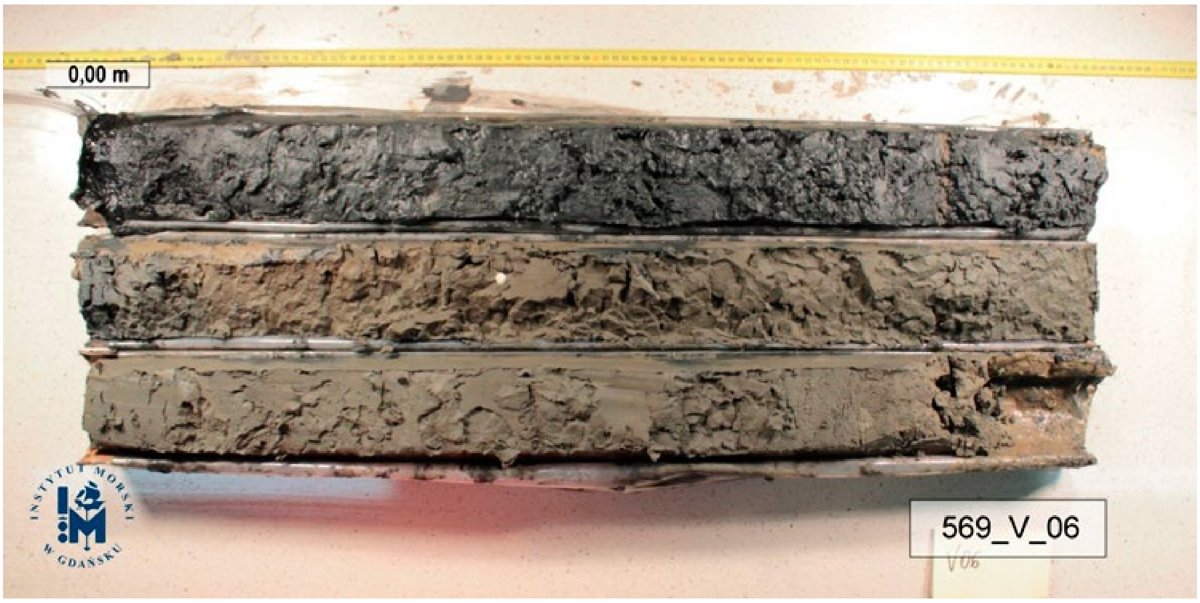

Figure 31. Sample core after preparation for geological analysis, before sampling for chemical analysis
(Source: Maritime Institute in Gdańsk)

After the photo is taken, the core is described macroscopically. The description consists of identifying the fraction (including additional elements such as, for example, parts of mussel, wood etc.), the way the components are placed, degree of sorting, humidity, colour, carbonate content, also the sediment firmness and plasticity depending on its type. It is a descriptive form of presenting the characteristics of the sediment, in accordance with the principles of macroscopic sediment description used in geology and geomorphology (Gradziński et al. 1986; Mycielska-Dowgiałło 1995, 1998). After macroscopic description, samples for granulometric analysis are taken from the main layers of the core (in Poland, these tests are conducted in accordance with the standards for geotechnical surveys: PN-EN ISO 14688-1:2006 standard: *Land analysis and classification. Part 1: Marking and description* and according to PN-EN ISO 14688-2:2006 standard: *Land analysis and classification. Part 2: Classification rules*). In addition, samples for chemical tests can be taken. In addition, samples for chemical tests can be taken from the core. They are analysed according to the same rules as the samples taken with a scoop.

4.9 Acquiring data using optical methods

4.9.1 Dane fotograficzne i filmowe

One of the modern methods of acquiring spatial information for building spatial models of wrecks and objects lying at the seabed, is the use of photographic cameras for taking hundreds or thousands of images of the wreck, according to a pre-established execution pattern. Above the wreck, a grid of lines is established (usually parallel lines, sometimes supplemented with a transverse grid to ensure 100% image coverage of the seabed) and it determines the path used by the camera carrier, i.e.: a diver, a ROV or an autonomous underwater vehicle, taking a sequence of photographs with at a fixed time interval. The condition for obtaining photographs suitable for machine processing is to cover the test area with photographs fulfilling the following conditions:

- subsequent photographs are taken at a fixed angle in relation to the seabed/object;
- subsequent photographs are taken at close distance (preferably fixed) from the object;
- photographed parts must have at least one common point appearing on two subsequent images (there are usually many more);

  subsequent photographs must have an overlap, i.e. a common area without any dead zones, both along the lines and between the lines.

The effectiveness of this method is largely determined by the water transparency and the prevailing lighting conditions. The more transparent the water and evenly distributed the light, the more details can be shown and the better spatial model can be executed. At present, the footage is often used by taking out some frames out of the film, with a fixed interval, e.g. every 5th, 10th frame. This interval depends on, among others, the speed of the camera movement above the object and the distance from the object during shooting (this in turn determines the size of the area covered by the camera lens). It is recommended to use lenses with medium focal length and high resolution frames (e.g. made in 4K technology). Underwater lenses must have high brightness, which allows to take multiple shots per second, and this in turn allows to reduce the blurring effect caused by the camera movements (by diver, ROV or AUV). Short focal lenses or the so-called fish-eye, allow to cover a larger area with the camera, but lead to many distortions, often impossible to correct and thus are not suitable for computer processing.

The 3D models made with this technology have the same or even better quality than laser scans, because they reflect the real colours and texture of the studied objects. They are cheaper because they do not require the purchase of any special towed laser scanners. However, there are a number of difficulties that must be overcome.

During the research carried out on the Franken shipwreck, it had not been possible to obtain a sufficient number of photos using this method, because the cameras were operated by divers, who could stay at the seabed only for a short time. Taking the photos, was a rather monotonous task, and additionally divers got trapped in the nets and lines suspended on the wreck, so the security level was decreased to an unacceptable level. Despite obtaining many valuable photos, it was not possible to produce even a small part of a 3D model. One of the main reasons for this was low water transparency and too little light. This generated many areas that did not correspond to each other and had no common points disabling the software to produce a mosaic and a coherent model.

The best results in acquiring data with optical methods can be obtained using a ROV that does not get tired. A well-trained ROV operator is able to control the area and quality of photographs. However, local conditions on some wrecks are a major obstacle, e.g. a large number of fishing nets, lines and other objects, strong local currents and other factors affecting the survey area, and thus – the quality of measurements.

Figure 32. Full 3D model of the HMAS AE1 hull. View from the starboard – a digital reconstruction of the HMAS AE1 wreck executed on the basis of approx. 8 500 photographs taken during an archaeological expedition in the beginning of 2018 (Source: https://phys.org/news/2018-06-secrets-hmas-ae1-shipwreck.html)

4.9.2 Photographic data showing oil spills (also from wrecks)

One of the important elements of activities related to wreck surveys are the observations of the traces left on the sea surface. It seems that the best source of such information are photos and videos taken with cameras placed above the water surface. Often the presence of wrecks is evidenced by fuel leaks visible from cameras of artificial Earth satellites, airplanes, drones or crew members of vessels in the wreckage area. Any such signs indicate that something has recently happened or is on-going. The visibility of an event depends on the scale of the leak and the amount of fuel:

- from space (i.e. from satellites) mainly massive spills are visible;
- small local leaks are visible from the planes or drones taking pictures from a height of several hundred meters;
- small leaks are visible from the bridge or deck of a passing vessel (although, of course, large leaks can also be observed in this way).

Some photographs from different camera carriers are presented below for comparison.

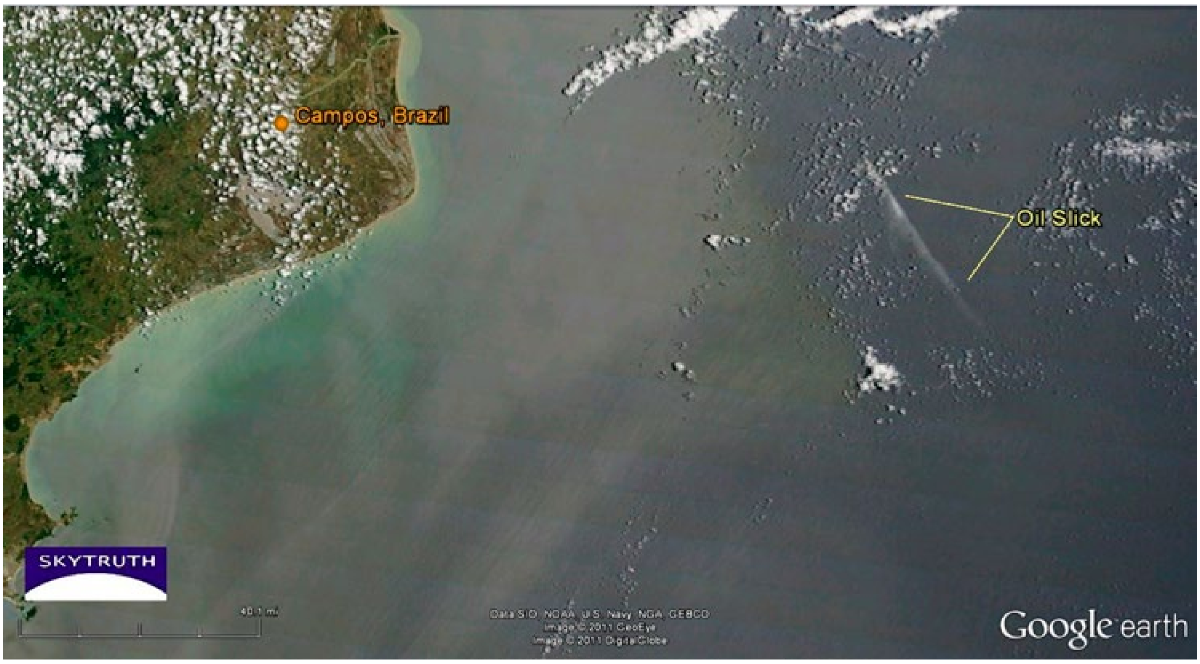

Figure 33. Oil spill image in the Northern Atlantic taken on 9th November 2011 r. Image by MODIS/ Terra from Campos, Brazil. Image obtained by the courtesy of NASA/Rapid Response Team (Source: https://skytruth.org/2011/11/oil-spill-off-brazil-seen-on-satellite/)

Figure 34. On the left, oil spill from the Franken wreck, on the right, the George Blucher wreck – photographs taken with a drone in September 2018 (Source: BalticTech Gdynia, Tomasz Stachura)

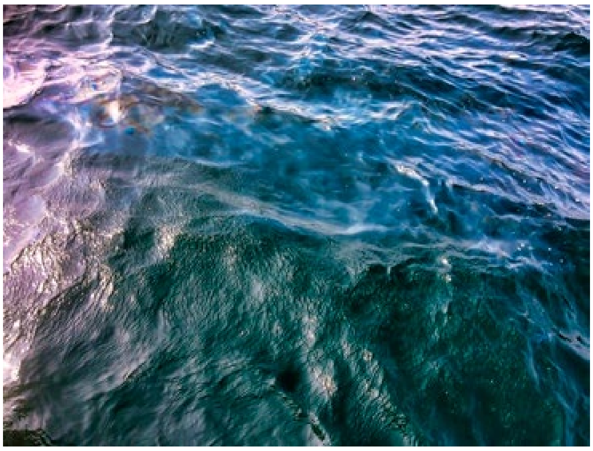

Figure 35. Oil spill from the George Blucherwreck – photographs taken from the S/Y Enduro in September 2018 (Source: BalticTech Gdynia, Tomasz Stachura)

4.10 Methodology of chemical and biological tests

4.10.1 Methodology for testing water, bottom sediments and marine organisms

If thorough analysis of the sea bottom around the wreck is to be carried out, laboratory tests of the sediments, water and marine organisms need to be conducted. Usually these surveys consist of the tests mentioned below. Tested parameters will allow for an objective assessment of the environmental status around the wreck at the time of the test. In order to use the survey results relating to the impact assessment of the wreck on the environment, there is a need to refer these results to the overall environmental status in the broad surroundings. Therefore, there is a need to carry out similar sampling in another place, quite distant from the wreck, called the reference point. Most often, survey results are compared with the data in available literature. However, in the case of a small sea such as the Baltic, with very variable local conditions and differentiated environmental status, referencing survey results to generalised data is not reliable. Experience shows that local conditions are very different. What is normal in one area, a few dozen kilometres away, may cause alarm because the environmental standards are exceeded. When determining the impact of a shipwreck on its surroundings, the influence of local conditions should be eliminated by setting standards. This does not mean that any exceedances of standards in the survey area can be neglected. It is possible that there are other, unknown source of contamination that should be identified. It can be concluded that when analysing the contamination on a given shipwreck, it is possible to discover another, sometimes much more dangerous source of contamination.

The following parameters are usually analysed in water samples:

- indicators of aerobic conditions; dissolved oxygen,
- substances particularly harmful to the aquatic environment (specific synthetic and non-synthetic contaminants): copper, zinc, petroleum (oil index),
- substances particularly harmful to the environment – priorities: cadmium, lead, mercury, polycyclic aromatic hydrocarbons (16 PAH), including: benzo(a)pyrene, benzo(b)fluorantene, benzo(k) fluorantene, benzo(g,h,i)perylene, indeno(1,2,3,-cd)pyrene.

The following parameters are marked in the surface sediment samples:

- loss on ignition,
- petroleum hydrocarbons (mineral oil),
- polycyclic aromatic hydrocarbons (16 PAH).

The following parameters can be marked in core samples of bottom sediments:

- humidity, loss on ignition, phenols, ether extract,
- metals: lead, chromium, zinc, cadmium, copper, nickel, mercury, vanadium, molybdenum,
- total organic carbon (OC),
- petroleum hydrocarbons (mineral oil)
- polycyclic aromatic hydrocarbons (16 PAH),
- polychlorinated biphenyls (7 PCB).

In samples of benthos organisms (*Mytilus edulis trossulus*) the content of the following substances are marked:

- metals (cadmium, lead and mercury),
- polycyclic aromatic hydrocarbons (fluorantene, anthracene and benzo(a)pyrene).

All physical and chemical tests of water and sediments should be carried out in an accredited laboratory, certified with an adequate certificate, e.g. Polish Accreditation Centre (PCA). The accuracy of the analyses should be checked by analysing, at the same time, certified reference materials for water and sediments (among others: QC SW3.1B and QC SW3.2B Nutrients in natural coastal/estuarine water- VKI Holland; QC 1297 Demand; QCI-711 Solids Samales, ONTARIO-99).

4.10.2 Analysis of near-bottom water

A water sample of approx. 1 litre is taken from the bottom layer, preferably not higher than 1 metre above the seabed for physico-chemical tests. Sampling points should be located around the area covered by the oil spill and in the area of lower spill intensity.

Water samples contain important information on dissolved chemical substances, as well as information on dissolved oxygen content, which is an indicator of water quality around the wreck and the environmental status.

Figure 36. Sampling water for chemical tests using a bathometer
(Source: Maritime Institute in Gdańsk)

Table 8. **Bottom water analysis from samples taken near the wreck**

No.	Analysis	Test method
1.	Dissolved oxygen	Titration, in accordance with PN-EN 25813:1997 standard
2.	Metals: Lead, copper, zinc, cadmium	Inductively coupled plasma atomic emission spectrometry (ICP-OES) according to PN-EN ISO 11885:2009 standard
3.	Mercury	Atomic emission spectrometry with amalgamation of mercury vapour according to PB-21 standard, 2nd edition of 14 June 2010
4.	Mineral oil index (concentration of petroleum substances)	Gas chromatography method with flame-ionisation detection (GCFID) after extraction of analytes from n-hexane water sample according to PN-EN ISO 9377-2:2003
5.	Polycyclic aromatic hydrocarbons (PAH)	Isolation and enrichment of PAH using SPE method (extraction to solid phase). PAH is marked with gas chromatography method together with mass detector (GC-MS). PB-02 procedure, 2nd edition of 10 May2007

4.10.3 Chemical analysis of benthos organisms

In the conditions of the Southern Baltic, the *Mytilus edulis trossulus* species of mussel is used to assess the level of contamination of marine organisms (due to its prevalence). Test organisms are collected from an area located at a distance of approx. 0.5 km from the subject wreck. *Mytilus trossulus Linnaeus* (European mussel) is a species widely distributed in the Baltic. It lives on any type of soil, with solid parts, such as sedentary seaweed, small pebbles, boulders and other objects at the sea bottom, such as slag, wood, steel sheets etc. The maximum depth at which the mussels form shoals corresponds to the lowest depth at which vegetation grows on the seabed (Mulicki, 1957). *M. trossulus* belongs to filter feeders and feeds on suspension and detritus. It is a food for some fish species, as well as birds (coots and ducks) wintering in the Baltic Sea. Mussels absorb pollution mainly through gills and with the food they consume. PAHs (polycyclic aromatic hydrocarbons) should also easily accumulate in the tissues of organisms due to their good solubility in fats. However, only consumers at the lower level (first-level consumers) of the trophic chain (mainly filter feeders, such as mussels) are exposed to high bioaccumulation. PAH concentrations do not multiply (biomagnification) when moving up the food chain. Consumers at the second and higher levels (fish, birds, humans) can quite quickly decompose these compounds (Staniszewska and Sapota, 2010). In the aquatic environment, organisms living at the bottom are the most vulnerable to the risks associated with the accumulation of heavy metals. Several times higher concentrations are observed in their tissues than in the surrounding environment. On the one hand some species are treated as excellent bioindicators, on the other hand, they constitute a potential source of contamination of organisms in the food chain. Heavy metals are permanently accumulated in the body of the next host and in consequence can also be dangerous for human health and life. Therefore, if possible, biological material should be taken for chemical analysis.

Samples of benthos organisms are taken with a trawl. After reaching a designated position in the survey area, the trawl is lowered to the bottom and towed a few dozen metres. One or two hauls are carried out in every position in order to get enough material for analysis. The selected mussel species is placed in containers with filtered sea water. Containers are placed for 24h in a laboratory in conditions similar to those in their natural habitat. Then, the organisms are deprived of shells, frozen and lyophilized. Such material is crushed in a grinder in order to get homogenous samples. The purpose of this survey is to determine the presence of benthos substances that penetrate the organisms from the contaminated environment, i.e. heavy metals, phenols, typical fuel compounds.

4.11 Biological analysis

Biological analysis comprises the qualitative and quantitative analysis of macrobenthos samples from the wreck surroundings, together with a description of the test results. The description of the results is done in terms of the qualitative and quantitative structure as well as ecological quality status of the survey area on the basis of macrozoobenthic communities.

Zoobenthos (bottom fauna) is composed of organisms living in the bottom sediments, both at its surface (epifauna) and the interior (infauna). Macrozoobenthos constitutes the biggest zoobenthic fraction in terms of the size of organisms. These animal organisms remain on a sieve with 1mm meshes during sifting of the sediment samples (HELCOM 1988).

Due to the relatively long life cycle, (most crustaceans live up to several months, while mussels live several years), macrozoobenthos is one of the best biological indicators for long-term changes in the environment. On the basis of the analysis of the occurrence and distribution of bottom fauna, conclusions can be drawn on the environmental status of the studied area (Żmudziński 1971). Ostrowski (1985) identifies three groups in the macrobenthos that characterise indicative species:

1. **Progressive species of the 1st level** – The group is composed of species considered as indicators of contaminants, showing high tolerance to pollution and salinity fluctuations. In the contamination zone, the populations of such species are dense and their biomass decreases as the source of contamination gets further away. This group includes: *Hediste diversicolor* and *Mya arenaria*.

2. **Progressive species of the 2nd level** – The group includes species that dominate in a moderately contaminated zone. They include: *Limecola balthica* and *Corophium volutator*.
3. **Progressive species** – The group includes sensitive species that do not tolerate and avoid polluted waters. They include: *Pygospio elegans* and *Bathyporeia pilosa*.

4.11.1 Material and method of biological analysis

Sampling

Macrobenthos collection sites are designated on the basis of the results of sediment sampling with a sampler as well as an analysis of the risk posed by the wreck to the marine environment. It is possible to conduct the analysis in the manner prescribed in advance, i.e. simultaneous sediment sampling for chemical and geological tests.

Figure 37. The content of the sampler collected at sites in the vicinity of the Stuttgart wreck in April 2016. At sites where heavy oil was macroscopically detected, no macrozoobenthos was found (photo 1 and 2), whereas macrozoobenthos was found in two remaining samples (photo 3 and 4) (Source: Maritime Institute in Gdańsk)

Samples are collected from selected sites with a van Veen sampler, with a grip surface of 1000 cm^2, with one repetition at each site. All samples should be described using a unique code, in order to permit identification of each sample, as shown in the Figure 37. On board the vessel, the content of the sampler is passed through a sieve with a 1 mm mesh. The residue is transferred to sealed plastic containers and preserved with a 4% formaldehyde solution. Despite the selection of sites from apparently 'clean' places with no trace of heavy oil, the collected samples may still contain fuel. Experience shows that if samples contain fuel identified in a macroscopic test on board the vessel in collected samples, they will not contain macrobenthos.

Analysis of macrobenthos structure

The Bray-Curtis formulae is used to determine the similarity of macrozoobenthos groups between sampling sites. It consists of the transformation of data on the population size through root extraction. The basic elements of the assemblage structure constitute the qualitative and quantitative composition of macrozoobenthos.

Graphic software, such as ArcGIS, is used to illustrate the size and biomass of the macrozoobenthos in the wreck area.

Assessment of ecological status

In Poland, the assessment of the ecological status of the survey area on the basis of macrozoobenthos is made using a multimetric index B (Osowiecki et al. 2012), whereas classification of the status is done on the basis of the limit values of water quality index as set out in the Regulation of the Minister of the Environment of 22 October 2014 concerning the manner to classify the status of surface water bodies and environmental quality standards for priority substances (Journal of Laws 2014 item 1482).

4.12 Ecotoxicological analysis

There is no need to conduct ecotoxicological tests in every case. Usually, there types of analysis are only carried out during the surveys of wrecks that have a very strong, negative impact on the environment. If an evident contamination of the surrounding area has been identified, there is a need to estimate how big is its impact. In any other case, conducting this kind of very costly research is pointless.

When conducting ecotoxicological analysis of core samples collected around a wreck, an analysis of soil toxicity is conducted with regard to three index species:

1. *Vibrio fischeri* bacteria (Microtox® test);
2. *Heterocypris incongruens* crustaceans (Ostracodtoxkit F™ test);
3. *Sorghum sacharatum* plants (Phytotoxkit test).

4.13 Ecotoxicological analysis – methodology

4.13.1 Determination of acute toxicity using marine bacteria *Vibrio fischeri*

This methodology refers to the approach used in toxicity tests in the vicinity of the very dangerous S/S Stuttgart wreck. There are certainly other methods of determining the indexes of negative (toxic) impact of contaminated sea bottom on the marine environment. This methodology has been tested with positive effect in the above mentioned case and will be used in surveys of other wrecks in Polish waters.

The Microtox ® acute toxicity measurement system is a system that works according to the standard methods of the ASTM (American Society for Testing and Materials) and PN-EN ISO 11348-3:2002 standard. The Microtox® test consists of acute toxicity measurements on specially selected luminescent strains of marine bacteria *Vibrio fischeri*, chosen for high sensitivity to a wide range of toxic substances. In normal conditions, bacteria *Vibrio fischeri* have the ability to produce light in the visible range (luminescence), which is the result of properly run metabolic processes. The change in the metabolism of bacteria cells has an impact on the intensity of the emitted light. In the Microtox® test, the toxicity is measured by examining changes in the luminescence intensity of bacteria *Vibrio fischeri*, exposed to the tested sample (aqueous extract), where the changes in the luminescence intensity are directly proportional to the biological activity of the sample. Luminescence is measured before and after incubation of the bacterial suspension with the tested sample (aqueous extract). The contact time of the sample with bacteria is 30 minutes. A diluted basic test is usually used: Basic Test 81.9%. The optimal pH value of the tested sample should be in the range from 6.0 to 8.5. Before toxicity measurements, the pH of the sample extracts is measured and, if necessary, it is set at an appropriate level by adding, as appropriate, a few drops of concentrated HCl and KOH solutions.

4.13.2 Chronic toxicity using Ostracodtoxkit F™ test

The Ostracodtoxkit F™ biotest was developed to assess the toxicity of sediments or soil contaminated with inorganic and organic chemical compounds. The Ostracodtoxkit F™ test is a “direct contact” test which enables an assessment of the overall toxicity of sediments, taking into account the impact of contaminants, both dissolved and undissolved in water. In the test, crustaceans *Heterocypris incongruens* hatched from cysts are exposed for 6 days to a thin layer of the tested sediment (1 ml), covered with a standard medium, on a multiwell plate. The final stage of the test is to identify two effects: mortality and inhibition of the growth of organisms exposed to the test soil sample in relation to the results obtained from a control sediment (reference sediment).

The analysis of chronic toxicity with the use of the ostracod *Heterocypris incongruens* was carried out in accordance with the Standard Operating Procedure. 1 ml of each soil sample was placed on a multiwell plate, the soil was treated with 2 ml of standard medium and 2 ml of algae suspension *Selenastrum capricornotum*. 10 test organisms were placed in each well, and the multiwell was incubated for 6 days. Each sample was tested in triplicate. After incubation, the average number of dead organisms and their average length was calculated in each sample and in the control sediment

.

4.13.3 Determination of toxicity using *Sorghum sacharatum* plants

The Phytotoxkit test uses plant seeds and was developed by the team led by Professor Guido Persoone from the University of Ghent, Belgium. The biotest is based on measuring the reduction (or absence) of germinating seeds and growth of young roots after several days of exposure of selected seeds to toxic substances or contaminated soil against control soil. The test was carried out in specially designed, flat and transparent test plates, consisting of two parts, the bottom part containing the test sample.

Plant seeds are placed on a paper filter lying on top of the sample (hydrated sediment). After closing the plates with a transparent lid, the plates are placed vertically on the rack and incubated at 25°C in the dark. The incubation time (minimum 3 days) depends on the seed germination time and the growth rate of the roots, which depends on the seed type.

The construction of the plate allows free growth of roots (downwards) and stems (upwards). At the end of the test, a picture of the plate with seedlings is taken. After incubation, the picture of the plate with germinating seeds is digitally recorded. The root length is measured using a software for image analysis Image Tool 2.0. The results are compared with the control sample, composed of seeds sown on reference soil and hydrated with a standard medium. Monocot sorghum (*Sorghum sacharatum*) was used in the tests. Each sample was tested in triplicate.

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CHAPTER 5: REVIEW OF AVAILABLE METHODS AND TECHNOLOGIES FOR REMOVING FUEL FROM SHIPWRECKS AND REMEDIATING THE CONTAMINATED SEDIMENTS

As a result of the amendment to the Environmental Protection Law (the provision had been added through a revision of 11 July 2014, Journal of Laws of 2014, item 1101) the term "**disposal**" has been replaced by "**remediation**". "Remediation" is used in this study in relation to measures aimed at removing or reducing the quantity, or controlling and limiting the spread of hazardous substances in soil and groundwater, so that a contaminated site stops posing a risk to human health and the environment, taking into account the current and future land use.

The law also states that, in justified cases, remediation may consist of self-recovery, if it brings more benefit to the environment. In practice, there are two basic options for recovering the contaminated seabed:

- ***in situ***
- ***ex situ***

In the *in situ* option, the remediation is carried out by disposing, stopping from spreading and capping the contaminated sediments on the site. In the ex situ option, the contaminated sediment is removed, transported and disposed outside the contaminated area.

Dredging is the most frequently chosen remedial approach for cleaning up contaminated seabed. In addition, a passive repair approach, often considered (at least temporarily) in many projects is natural recovery, consisting of intrinsic removal or isolation of contamination in the sediment from biological receptors, through a combination of naturally occurring physical, chemical and biological processes (Hull et al., 1999). Other removal technologies are based on pumping fuel out of the tanks of a problem wreck. Additional on-site disposal technologies include: *capping*, i.e. isolating the contaminated area by covering or backfilling the contaminated sediment; separation of contaminated area with a wall to limit the movement of fuel; as well as solidification and stabilization of the contaminated sediments with natural substances (e.g. ash) or other chemicals. In the case of organic contaminants, bioremediation may also be used to accelerate natural microbiological degradation.

Methods for removing contamination or for remediating contaminated sediment that may be taken into account in the case of the Stuttgart shipwreck are described in the following sub-chapters and include:

***in situ*:**

- monitored natural recovery,
- separating contaminated area with a fence,
- solidification and stabilisation of contaminated sediment with fly ash or other binders,
- capping the contaminated area,
- bioremediation;

***ex situ*:**

- removal of contaminated sediment by dredging,
- *hot-tapping* and pumping fuel residues from the wreck with ROV and divers.

In selecting the clean-up and pumping methodology for a wreck, the need to use other technologies should also be considered to assist the sea bottom clean-up and to protect against secondary contamination. These might include:

- booms,
- skimmers,
- oil, water and sediment separators,
- mobile and floating tanks,
- burning oil on water surface.

5.1 Monitored natural recovery

A passive, *in situ* cleaning method is a natural (intrinsic) sediment cleaning. The term **monitored natural recovery** (MNR) is defined by the *National Research Council* as a remediation to protect the environment from unacceptable exposure to contaminants on the basis of natural environmental processes (ITRC, 2014). This method consists of leaving the contaminated sediment in place and using the natural processes, such as:

- turning the contamination into less toxic form (e.g. biodegradation),
- binding the contamination closer to the sediment (e.g. sorption),
- capping contaminated sediments with a clean sediment (e.g. sedimentation) (U.S. EPA, 2004).

Leaving the oil to naturally decompose can be the most environmentally friendly solution. There are known cases where measures taken as a response to an oil spill have resulted in much more serious environmental damages than the oil spill itself (Preston et al., 1997). This option is particularly recommended in sensitive, unique ecosystems that could be irreversibly damaged by isolating or dredging (U.S. EPA, 2004). The most favourable conditions for the implementation of this solution are areas where bottom sediments are quite stable and resistant to suspension in the water column (in such case the contaminants are easily biodegradable or can be converted to lower toxicity forms) or the concentration level of contaminants is low, they cover dispersed areas and have low bioaccumulation (U.S. EPA, 2004). In addition, natural recovery is most effective in deep water bodies with slow water exchange.

Natural recovery is often used in connection with other methods as a complementary method (or an alternative) to conventional recovery. Biodegradation, sedimentation, recovery modelling and long-term monitoring are used as part of this method. There is an option for enhanced natural recovery, consisting of placing a thin layer cap of clean sediment and/or adding an active substance. Such methods accelerate the natural recovery process as a result of mixing with clean sediment. The addition of an active substance in the form of activated carbon or organic clay to a layer of clean sediment further reduces the migration of dissolved contaminants in the pore water by binding them in the absorption process (U.S. EPA, 2005).

The decision to implement natural remediation should be the result of thorough analysis of the area and contaminant characteristics, the modelling of environmental processes and long-term monitoring of the area (Magar, Wenning, 2006). Contamination control and monitoring by sampling water and sediments as well as the tissue of organisms are also required to ensure that the recovery process is taking place as result of the used solution. The monitoring requirements for monitored natural recovery are presented in the guide of *The Interstate Technology & Regulatory Council* (ITRC, 2014).

Examples of use

Many cases of successfully applied monitored natural recovery are outlined in the *Technical Guide: Monitored Natural Recovery at Contaminated Sediment Sites* (Magar et al., 2009). One of the examples is the Hartwell lake in South Carolina, where natural capping of the contamination together with biodegradation of heavier PCBs to lighter PCBs occurred. Samples of surface sediments taken every year indicate an improvement (Magar et al., 2009).

Costs

The remediation costs on the basis of natural environmental processes include only monitoring and were classified by the *National Research Council* as low (below 1 $\$/yd^3$, that is 1.3 $\$/m^3$). In the case of the area contaminated around the S/S Stuttgart shipwreck (approx. 400 thousand m^3) costs would amount to 520.000 dollars.

Advantages

The undisputed advantage of monitored natural recovery, as compared to other methods, is that it does not affect the existing biological communities. This method does not cause any risk of sediment disturbance and their dispersion. The low cost of this method results from the lack of demand for specialised equipment, e.g. to remove and transport the sediment. The total cost of natural recovery includes long-term, detailed monitoring of the environment and contaminants (U.S. EPA, 2004). Monitored natural recovery under appropriate environmental conditions is associated with low risk and high level of effectiveness and sustainability (Magar et al., 2009). This method does not generate waste. It is recommended in areas, where dredging and capping are not possible, such as vast areas with relatively low contamination (ITRC, 2014).

Limitations

Degradation of contaminants without interference can be slower than with active recovery methods and usually takes between 5-30 years. There is a possibility of secondary contamination of the ecosystem as the fuel remains in place. Natural phenomena, such as storms, may cause further dispersion of contaminants. In addition, there might be a need to exclude the area from fishing for a long period of time. In some cases, the degradation products may be more harmful than primary contaminants (Staniszewska and Sapota, 2010). Additionally, the lack of corrective measures is perceived by the society with doubts as to the effectiveness of this method. Monitored natural recovery may be more readily accepted if used alongside other recovery methods (U.S. EPA, 2004).

In the case of activities around the S/S Stuttgart wreck, there are significant doubts as to whether this method can be considered useful and be consequently used as an effective solution to the problem. The main reasons for this are:

- lack of information on the processes taking place in the contaminated area over the period of several years, such as:
  - increase/decrease of the contaminated area,
  - sedimentation processes occurring in the area and the associated natural backfilling / uncovering of contaminated soil,
  - processes of penetration of fuel into the seabed are unknown.
- long-term surveys of the substances contaminating the seabed (to allow a clear view as to whether degradation products are less harmful than the fuel itself) have never been conducted;
- there is no information about the chemical processes in the fuel that had leaked from the Stuttgart shipwreck;
- there is no information about the amount of fuel in the wreck tanks and what amount of fuel is constantly "feeding" the contamination area;
- there are no results from long-term surveys and no information about the impact of contamination (including cancerogenic processes) on the fauna and flora in the contaminated area.

5.2 **Separating the contaminated area with a fence**

It is possible to stop the fuel spill on the seabed by placing a fence around the contaminated area. The fence may be made of elements combined into a waterproof wall made of iron or steel, the so-called Larssen piles. However, this is a solution for small and shallow areas. Most often, the wall is made in the form of a cofferdam, in order to separate the contamination source from the surroundings.

Examples of use

This method was used on several wrecks. Most often, the so-called dry cofferdam is used with the possibility to pump out water around the object inside the fence. An example of a cofferdam built around a wreck is the cofferdam round the S/S Catala wreck (www.ecy.wa.gov), as well as a cofferdam used during archaeological research on La Belle (Figure 38).

Another option is to surround the area with an embankment. Preserving such an embankment may be difficult in a dynamic environment where there is a risk of damage during storms. This solution had been proposed for the DBL-152 wreck, but it was found that it would not be a sufficient protection against the oil spill as it would likely bypass such a construction (IMO, 2011).

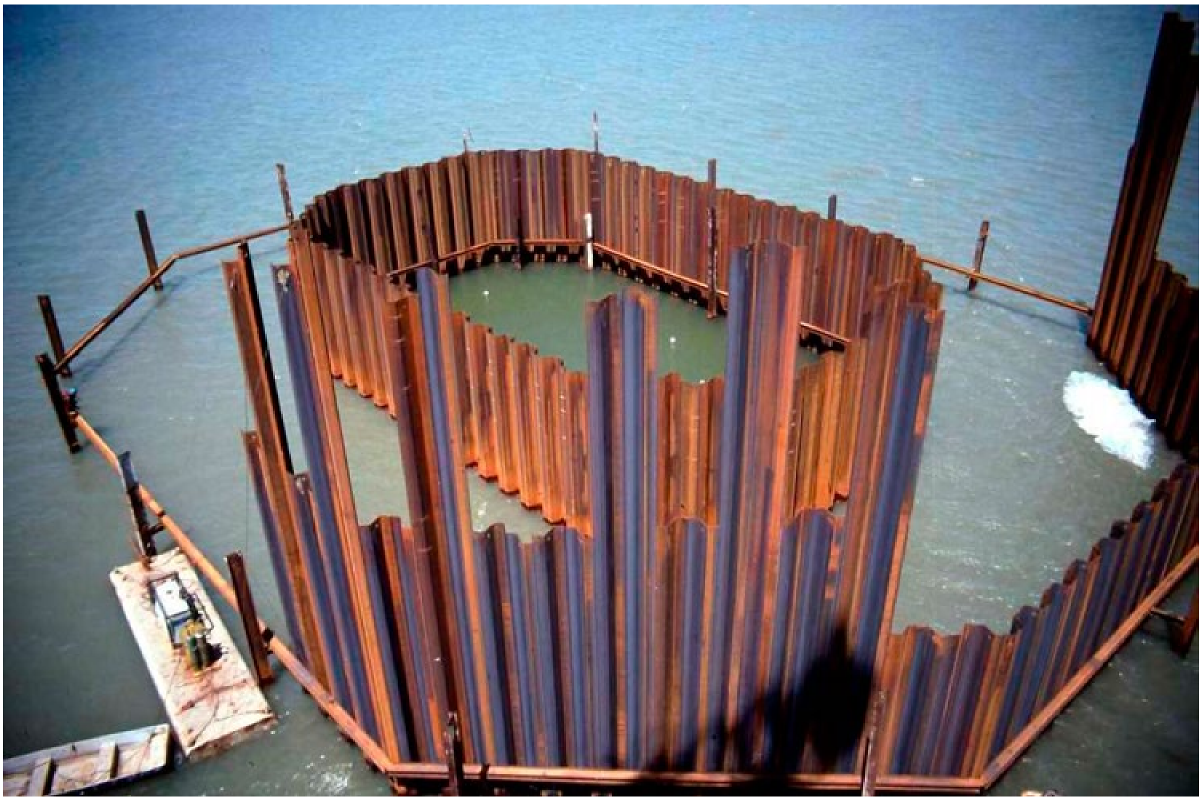

Figure 38. Construction of a cofferdam made of steel walls around the La Belle wreck
(Source: www.texasbeyondhistory.net)

Costs

The costs of using the separation method include the cost of material, transport and equipment to install the cofferdam/embankment. Due to the use of expensive components, this method is one of the most expensive.

For example, in the case of the archaeological survey of the small La Belle wreck (less than 17 m in length), the cost of building a dry cofferdam in 1996 in the form of a double steel fence filled with sand in-between the two walls, amounted to 1.5 million dollars (Viduka, 2012).

Advantages

The advantage of separating the contaminated area together with the wreck is the possibility to stop the spread of oil on the seabed, while allowing the contamination to biodegrade. This method is less invasive for the environment than dredging and removing the sediment. In addition, a cofferdam permits to separate the contaminants in the water column and, in favourable conditions, i.e. at small depths and with a small area to be fenced, to dry the area and carry out a safe remediation, without the risk of releasing the contaminants into the environment (Renholds, 1998).

Limitations

The biggest limitation of this method is the high cost of such structures. Moreover, this method does not completely stop contaminants from entering into the sediments. There is also a risk of release of contaminants into the water column during storms.

In the case of the S/S Stuttgart wreck, this method cannot be considered useful and consequently cannot be used as an effective solution. The main obstacles are:

- very high cost of constructing the Larssen cofferdam:
  - the need to employ specialised personnel for several months, or even more than a year,
  - extraordinary length of piles (over 35 metres), currently not available on the market,
  - amount of material needed for a cofferdam is estimated at not less than one million tonnes of steel to build a wall of approx. 4 km,
  - assuming that the wall would be double, the time and the amount of material would also double, and therefore the costs would be three times higher,
  - the need to dry the area would involve a huge amount of additional equipment and the costs (e.g. of energy) are difficult to estimate;
- relatively high depth around the wreck (approx. 22-23 m), and 22-27 m on the north-eastern border,
- uncertainty that the cofferdam would ensure complete tightness,
- lack of experience in building such fences (of such height and length – nowhere in the world has this solution on such a scale been used), would generate the need to establish an effective and safe method of building the structure. This would require significant research and would generate huge costs that are difficult to estimate,
- huge risk of failure in constructing such a barrier under the present state of knowledge and available technologies.

5.3 Solidification and stabilisation of contaminated sediment. Use of fly ash

The next available remediation method is based on two processes, solidification and stabilisation (hardening) of sediments. Stabilisation is a chemical process that leads to the disposal of contaminants by converting them into less soluble, less mobile and less toxic forms and is applicable to components capable of chemically binding and reacting with a stabilising agent (Wittenberg et al., 2013). Solidification is a physical process, binding the contaminants with a binder. This process binds contaminated sediments and detoxifies them through physical isolation to a solid form. Solidification of sediments prevents erosion and release of contaminants (Renholds, 1998; Schifano, 2015).

Portland cement, lime and fly ash from coal combustion, and mixtures of these components in various proportions are all used as binders. The best solution is to use fly ash, a product of coal combustion from power plants. Ash deposited on electrostatic filters is the size of dust, in a very shredded form. It has the ability to swell and harden in water, which it easily absorbs. Such properties allow it to easily penetrate into crevasses and rubble and produce a stable, non-settling sealing surface (google.pl/patents/US3500934 and Ansary et al., 2006).

On the basis of chemical composition, depending on the type of carbon burned, two classes of fly ash can be distinguished: F and C. Class F is derived from a combustion of anthracite or bitumen carbon, and class C ash is a remnant of the combustion of subbituminous carbon and lignite. Class C ash has self-sealing properties. Therefore, it can be used independently to harden moderately plastic sediments without the addition of activators, such as lime or cement (Geliga, Awg Ismail, 2010). Demirkan (2014) indicates the ability of class F ash with high content of carbon to absorb various organic contaminants and its effectiveness in stabilising oil pollutants. Bone also confirms the impact of high carbon content on increased ash absorption (2004).

The stabilisation and solidification method requires the mixing of contaminated sediment with the binding substance. Mixing conditions and curing temperature are important factors affecting the strength of solidified sediments (Renholds, 1998). Mixing is an important stage of the process. Conditions hampering the mixing process could consist of excessive heterogeneity of disposed sediment and uneven dispersion of the material in the mixture. Application of the substance should ensure good mixing of the binder with the sediment. At the same time, when mixing the sediment with the binder, contaminants are dispersed in the water column and surroundings. The solution to reduce the resuspension is the injection of ash into the hazardous substance using a special device called an injection bar (Renholds, 1998). The ash may also be pneumatically injected into any surface using a string of pipes (Lahtinen et al., 2014).

One of the latest solidification technologies consists of using special sulphur polymer – Sulrock. This technology is now being developed by **Professor Bohdan Zakiewicz**.

The most important features of the material are its mechanical properties, such as: high resistance to pressure, stretching, bending, abrasive wear and a negligible impact to temperature fluctuations (in the atmospheric range). A very favourable distinguishing feature of Sulrock is its chemical stability - the material does not change or degrade under the influence of aggressive chemical compounds, such as acids, oils and petroleum derivatives, salts and their solutions. The passage of time also negligibly affects the fatigue and aging of the material. For some time after the release of the material, an improvement in the mechanical properties of Sulrock can be observed.

Examples of use

Fly ash is most often used on land as a binder to soil stabilisation in construction works and on dumping grounds and areas contaminated with various pollutants, including petroleum products. Ash is also used to stabilise sediments when dredging the seabed (Lahtinen et al., 2014). However, most of the application examples relate to stabilisation on land. The injection of ash or an ash-cement mixture into the bottom sediments has been done on a small scale, in only a few cases (e.g. Manitowoc Harbour and Manitowoc River, Hamilton Harbour, Fox River and Hama River [Renholds, 1998; NRC, 1997]).

This technology has never been used on marine sediments in situ. On the other hand, laboratory tests confirmed the effectiveness of fly ash on sediments contaminated with petroleum products. The results of the research conducted by Chan (2014) on marine sediments, after adding coal ash, indicate a good binding effectiveness as well as a reduction in pH (alkalising properties). Also, Schifano (2015) confirms the ability of class C ash to bind and absorb hydrocarbons in areas with very high concentration of oil and grease. Another publication by Srivastava et al. (2009) examines the effects of mixing fly ash with clay soil contaminated with diesel engine oil. The results of this research confirmed the effectiveness of fly ash as a binder. Yet, the mixture improved the properties of soil only to some extent. In turn, Banerjee (2005) proposes to modify fly ash with hexadecyltri-methylammonium (HDTMA) cation. According to him, ash can be successfully used in the process of oil remediation. Modification of ash with the use of the HDTMA cation, changes its properties - from hydrophilic to organophilic. This process significantly increases the absorption efficiency. Fly ash modified with HDTMA cation has been shown to be effective in removing dissolved organic carbon present in decomposed oil contaminating marine water (Banerjee, 2005).

Costs

The costs of the fly ash material from carbon combustion range between 15 and 40 US dollars per tonne or from 0.75 to 2 cents per pound (www.concreteconstruction.net). However, the highest costs are incurred by the transport of the raw material and its processing (preparation for use at the injection site). A long distance from the source of the raw material extraction can double or triple the price of fly ash application (www.concreteconstruction.net). Mackiewicz and Ferguson (2005) estimate the costs of delivering fly ash at 18-30 US dollars per tonne, depending on the source of the ash and local transport distance.

Advantages

The procedure with the use of fly ash can lead to the transformation of pollutants into less soluble and less dispersed or less toxic forms (Renholds, 1998). Ash may be successfully used as an alternative cost-effective binder to increase the resistance and to immobilise metallic and organic contaminants (Schifano, 2015). It is an environmentally friendly solution involving the use of a waste by-product of coal combustion, the management of which is a problem (www.spalanie.pwr.wroc.pl).

Limitations

The stabilisation and solidification processes do not remove pollutants, but slow down the process of their negative impact on the environment or prevent the migration of pollutants to the environment (Wittenberg et al., 2013). The application may be a technological challenge. It is difficult to ensure good mixing, which is the main factor in stabilisation, without releasing a certain amount of contaminants into the water. The control of the process may be limited. Moreover, the degree of resuspension is lower than during the use of technologies to remove contaminated sediments (Renholds, 1998). It is also difficult to ensure uniform doses of the binder.

There is little experience with the application of this technology, not sufficient enough to estimate the costs of applying the technology on a large scale, assess efficiency or predict possible toxic by-products of the stabilization process (NRC, 1997).

In the case of the S/S Stuttgart wreck, this method can be considered useful and consequently used as an effective, but a partial solution to the problem. The main drawbacks of using this method are:

- high cost of materials used (approx. 200 thousand m³ of concrete/mixture of ashes with cement are needed to cover 415 thousand m² of contaminated area),
- high cost of the use of specialised equipment and works,
- lack of knowledge on technical conditions to be met – further studies are needed,
- lack of certainty that the protective layer will be flexible enough and at the same time strong enough to maintain complete tightness,
- lack of knowledge on biological effects of such interference in the seabed (temporary or permanent elimination of macrozoobenthos from the cap covering the contaminated area)
- to date, this solution has never been applied on such a large scale, anywhere in the world.

5.4 Capping the contaminated area

Capping consists of covering contaminated sediment with a layer of clean material, which remains in place to isolate the contamination from the environment. The cap may consist of clean sediments, sand, gravel or stones. A more complex cap may contain geotextiles or other synthetic material and other permeable or impermeable materials used in multiple layers. The caps may contain an addition of an active substance, in the form of organic carbon or other modified forms to slow down the flow of contaminants (U.S. EPA 1998; U.S. EPA, 2004). In total, three types of caps can be distinguished:

- **conventional capping** – consisting of sand or other natural materials, directly on the contaminated layer of sediment,
- **reinforced capping** – with an additional layer of stones or backfill to provide additional protection against high velocity currents,
- **composite capping** – composed of several layers of sand, stones and geotextile, providing better isolation.

Such capping isolates physically contaminated sediment to reduce direct contact with organisms buried in the sea bottom, reduces bioturbations, stabilises contaminated sediments, prevents dispersion and displacement of contaminants to other area, and chemically isolates the contaminants to reduce the dissolved contaminant flow to the water column (U.S. EPA, 1998, Himmelheber et al., 2008).

Capping is used in cases, where removal of the contamination would be too expensive, impractical or could cause further spread of contamination. The method may also be effective as a provisional measure, until effective cleaning methods are found (e.g. if the oil leakage in the water is limited to one zone and remains stable; Fitzpatrick, 2013). This technology is best suited to retain volatile and semi-volatile organic compounds (including polychlorinated biphenyls, PCB and polycyclic aromatic hydrocarbons PAH), pesticides and metals (www.cpeo.org). Capping is also used if the source of contamination is significantly weakened or when the natural purification process is too slow. Another factor supporting the choice of this method is the availability of an appropriate type and quantity of suitable capping material (NRC, 1997).

A prerequisite for the use of capping for contaminated sediment is the cessation of the original leakage as well as hydrological conditions not causing surface disturbances of the seabed, because strong currents could move the capping materials. An important factor is the availability of the capping material and the resistance of the seabed in the location of the cap, because it must maintain the capping. The depth of the seabed is another important factor, because capping may reduce the space available for water traffic (www.cpeo.org).

The cap should be composed of an inner layer with grains increasing towards the bottom, in order to prevent collapse of the heavy material. It is also necessary to reduce the permeability of the capping by using an additional impermeable and erosion-resistant outer covering or by injecting a surface hardening agent into the surface cap (e.g. cement or fly ash) (Alcaro et al., 2007). When using a geotextile layer with an active substance in the cap (e.g. organic carbon or organic loam), the material is supplied in a rolled-up form, placed on contaminated sediment and covered with sand or other conventional capping material of suitable thickness to ensure a suitable habitat for benthos (U.S. EPA, 2004).

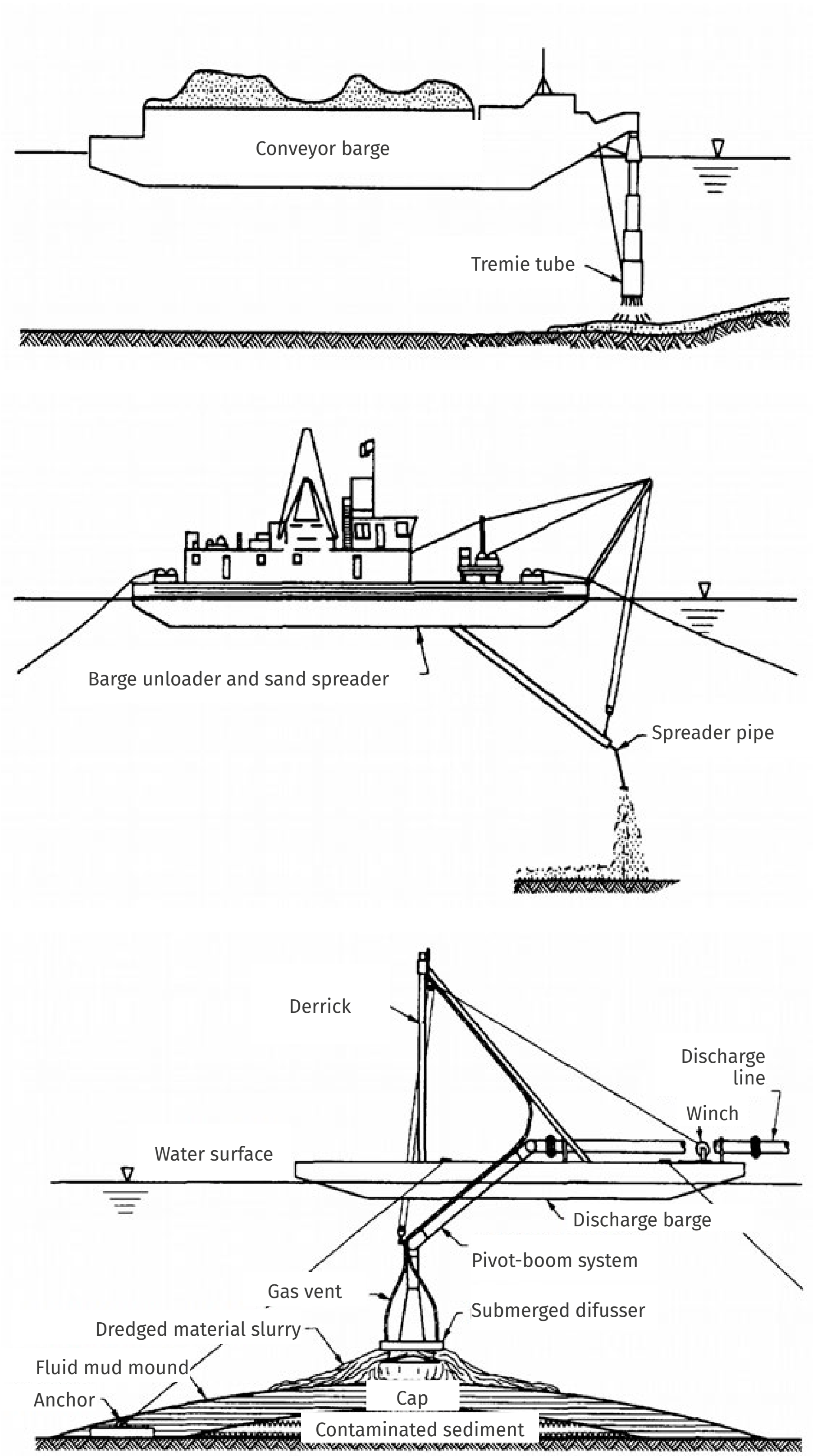

Figure 39. Equipment to deliver the capping material: discharge barge, barge with spreader pipe, barge with a *tremie* tube (Source: U.S. EPA, 1998)

Examples of use

The capping material can be placed on the seabed from a barge with a conventional hopper dredger or using a submerged diffuser with a pipeline, a *tremie* pipe (Figure 39) or a pipeline connected with a ROV equipped with cameras (Figure 40). More illustrations of machines used for capping can be found in the document of the EPA and *Army Corps of Engineers* (U.S. EPA, 1998; U.S. ACE, 1998).

Capping has been used to remediate sediments contaminated with different substances (among others, petroleum compounds), including marine areas near the shore. The documents U.S. EPA (1998), U.S. ACE (1998) and ITRC (2014) contain examples of projects using capping of different structures to contain varying contaminants, including petroleum compounds.

The capped area requires long-term monitoring to verify the integrity of the cap and to ensure that the contaminating substances do not migrate.

Another option consists of encasing a wreck and adding a concrete cover. This solution was considered in cases requiring extensive cleaning or where the cleaning operation could pose a substantial risk, especially in the case of war wrecks with numerous unexploded ordinance at the sea bottom. Capping of the entire wreck was suggested in the case of the USS Montebello and the German U-boat: U-864 (Barrett, 2011).

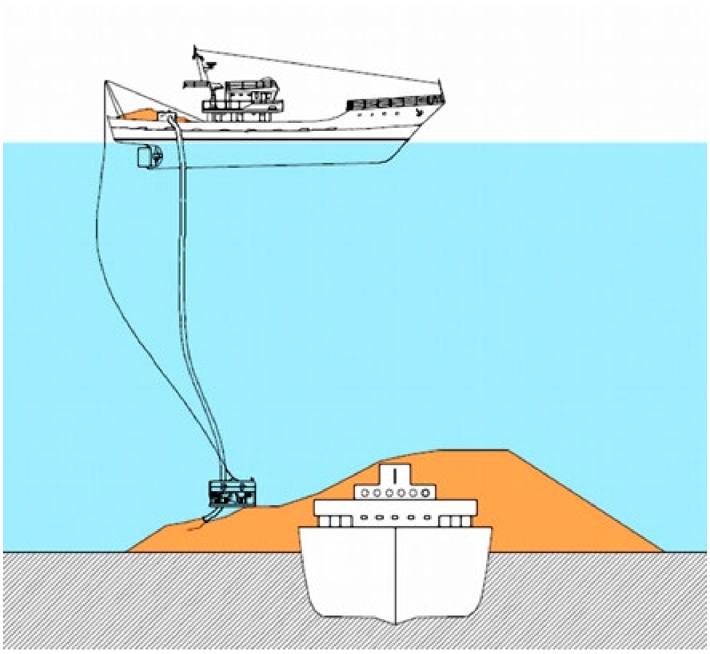

Figure 40. Capping the wreck with the use of ROV (Source: Alcaro et al., 2007)

Costs

The costs of capping include the costs of material, transport, storage and application, as well as the monitoring carried out during and after the operation in order to control the capping and contaminants. The basic cost of the material is mainly affected by its availability and transport costs.

The National Research Council categorises the capping costs as moderate and estimates the costs at 1 $\$/yd^3$, that is 1.3 $\$/m^3$ (NRC, 1997). Additional costs are associated with possible modifications and improvements of the capping, such as, for example, addition of active carbon or the use of an active capping mat. The EPA publication estimates the costs of such modifications to be approx. 35 $\$/m^2$ (2013).

Based on the information on current prices of collection, transport and placement of 1 m3 of the seabed sediment (sand, loam), received from the Maritime Office in Gdynia and from dredging companies that carry out dredging operations in the area of the Gdańsk Bay, the estimated costs of such an operation amount to 6-12 EUR/m³. The costs of additional materials (e.g. geotextile) and their deposition are not included in the estimate.

Advantages

Capping isolates the contaminants and minimises their dispersion. Moreover, capping of contaminated seabed with clean sediment provides stable geochemical conditions and supports chemical and biological degradation of contaminants, in particular, if the material contains active compounds (Alcaro et al., 2007; NRC, 1997). A sandy cap can provide a clean habitat for the re-colonisation of organisms (Hull et al., 1999). This method is minimally invasive, does not cause significant damage or permanent removal of the benthos. In addition, a well-designed and placed cap should reduce the risk for fish and other organisms and create desirable (aerobic) conditions by changing the sea depth (Himmelheber, 2008). In relation to dredging, capping does not cause significant disturbances in the sediments or the water column and eliminates the risk of suspension, dispersing or leaking of the contaminated sediment. The method is relatively uncomplicated and does not require the removal, disposal and deposition of the sediment. The operation is usually quicker than sediment removal and less costly. It requires less equipment, fewer specialised tools and uses locally accessible materials (U.S. EPA, 2004, Himmelheber, 2008).

Limitations

There is a risk that after placing the first layer of the capping material, the sediments may be released to the water column and as a result of consolidation create a mass flow (www.cpeo.org; Himmelheber, 2008; U.S. EPA 2005). Capping may be difficult under certain conditions without disturbing the contaminated sediment. The contaminants remain in the environment and may be released when the cap is moved (as a result of stronger currents and waves, which may cause faster erosion of the cap). This can be prevented by using a capping reinforced with a layer of a thicker material. Another disadvantage of capping is the potential affect it may have on the habitats of benthic organisms (Himmelheber, 2008). Capping with clean sediment weakens the primary contamination, which is important for the subsequent removal or remediation of sediments. The capping requires constant monitoring of its integrity (NRC,1997). Restrictions in maritime traffic may be required (U.S. EPA, 2004).

In the case of the S/S Stuttgart wreck, the method may be considered an effective and comprehensive solution to the problem. The main reasons are:

- relatively low cost of the materials used (it takes approx. 400 to 800 thousand m³ of sand to cover 415 thousand m² of contaminated area),
- relatively low cost of the operation, because of a standard (low) cost of equipment and work technology,
- widely available knowledge on technical conditions to be fulfilled,
- positive experiences related to the biological effects of such an interference with the sea bottom (despite the destruction of the original benthic fauna, there is no risk of permanent elimination of macrozoobenthos in the area around the capping placed over a contaminated area, due to its fast restoration),
- no permanent restrictions for navigation in the capping area (restrictions only during the backfilling of the protective layer),
- small risk of secondary contamination of the sea bottom and water during the operation,
- no time limit (the operation can be carried out at any time of the year, preferably in winter, there is no need to complete the operation all at once),
- possibility to combine several dredging investments with wreck capping, e.g. the planned fairway to the Northern Port and the container terminal in Gdańsk,
- the disadvantage is the lack of certainty that the protective layer will be sufficiently flexible and at the same time durable so as to maintain full impermeability, therefore there is a need for additional

(multiannual) surveys of water currents and waves and their impact on the capping, as the protective layer.

- to date, this method has been used with positive results to limit oil contamination on the seabed, although nowhere in the world has this solution been applied on such a large scale.

5.5 **Bioremediation**

Bioremediation consists of the use of microorganisms or their enzymes to decompose organic contaminants such as petroleum and petroleum products, aromatic hydrocarbons, benzene, toluene and xylene, PCB (polychlorinated biphenyls), PAH (polycyclic aromatic hydrocarbons), chlorinated phenols and several pesticides (NRC, 1997). Some microorganisms naturally present in the contamination area may prove ineffective in degrading oil contaminants or may decompose them too slowly (Renholds, 1998). In this case, the following procedures are used to help initiate and accelerate the decomposition rate of contaminants:

- **biostimulation** – consists of providing nutrients (usually nitrogen and phosphorus) to stimulate the growth of microorganisms,
- **bioaugmentation** – consists of introducing additional microorganisms degrading the hydrocarbons and feeding ground for microorganisms (Walker et al., 2003).

The effectiveness of bioremediation depends on many factors, primarily on effective mixing of the product into the sediment and the quantity of microorganisms, media, oxygen, and moisture It may take a considerable amount of time (from months to years). Degradation takes place faster in warm temperatures (>15.5°C), in natural pH and on large contaminated areas (Walker et al., 2003).

The best solution to prevent a dispersion of the contamination during mixing of sediments with microorganisms and the feeding ground, is application consisting of direct injection of the substance into the sediment or putting the substance into a fixed carrier, which can be placed in the sediment, such as in the microencapsulation process (Renholds, 1998).

Examples of use

Bioremediation studies have been conducted on soils for many years. In 1989, for the first time, a large-scale bioremediation was carried out *in situ*, on a rocky beach contaminated with petroleum after the accident involving the *Exxon Valdez* oil tanker in Prince William Bay in Alaska. Research has shown that fuel biodegradation can be simulated by the addition of nitrate and phosphate (Alaska Oil Spill Commission, 1990).

In the case of marine sediments, bioremediation efficiency was mainly studied under laboratory conditions. One example is the experiment carried out in anaerobic conditions in a tank filled with sediments and sea water taken from the port in Messina. Heavy bunker C oil was applied to the sediments and monitored for 3 months. After 3 months, the oil was capped with clean sediment. Then, aeration was applied to initiate self-remediation process. For the following 3 months, the condition of native bacteria in the sediment and the degree of oil decomposition, as well as the hydrocarbon products were studied. At the end of the experiment, the contaminated sediment showed 98% breakdown of the total hydrocarbon and almost total extinction of the bacteria responsible for hydrocarbon degradation. The toxicity of sediments decreased significantly. The results indicate the effectiveness of the aeration process in initiating the self-remediation of sediments contaminated with petroleum products (Genovese et al., 2014).

An example of successful in-situ bioremediation on sediments was carried out on the Dofasco Boatslip in the Port of Hamilton, Canada, where anaerobic bioremediation was performed using microorganisms naturally occurring in the port's ecosystem, using chemical injection of oxidants and nutrients. An 8-metre applicator, placed on a boom, was used to inject chemical substances directly to the bottom sediment

(Figure 41). According to laboratory research on sediments from the Hamilton port, microorganisms degraded almost 78% of the oil in 197 days (Renholds, 1998). However, according to other sources, the effectiveness of this procedure is questionable (NRC, 1997). The NRC states that this method has not been sufficiently demonstrated and the proposed *in situ* application scenarios into the sediments may cause many difficulties.

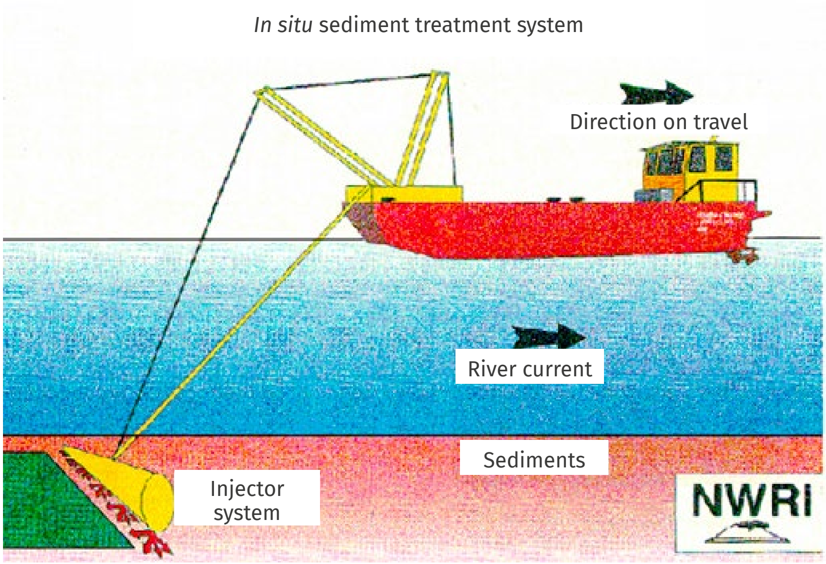

Figure 41. Sediment treatment system in the Hamilton port in Canada
(Source: National Water Research Institute)

Some examples of the use of bioremediation after an oil spill from ships are described by Swannell et al. (1996). However, in many of these examples bioremediation had only a slightly positive impact on the state of the bottom environment and there is no clear evidence of its effectiveness. According to the authors, bioremediation should not be used as the first response to the fuel spill, but in combination with other, more effective technologies, especially if there are important reasons to quickly carry out the remediation (Swannell et al., 1996).

Walker et al. (2003) propose to carry out bioremediation after other methods had been used, e.g. after destructive, inefficient and costly extraction of contaminants.

Costs

Due to little experience with application of in situ bioremediation on marine sediments, there is not enough information about the costs of carrying out such a procedure in the marine environment. For example, the total costs of a remediation from PCB with active microbes in the Hudson river amounted to 2.5 million dollars for 3 m^3, the cost of encapsulation ranged from 50$ to 60 $/$yd^3$ (66-79 $/$m^3$) of contaminated sediment (NRC,1997). In comparison, the cost of bioremediation carried out on land amounts to 30-100 $ per m^3 of land, depending on the type of soil and its chemical properties, as well as the type of improvements applied and the type and range of the contamination (www.frtr.gov).

Advantages

Bioremediation is an environmentally friendly method. It uses processes naturally occurring in the ecosystem in order to eliminate contamination on site and causes minimal physical disturbance to the environment. It is potentially one of the least harmful and costly methods of removing petroleum products. It requires less equipment and personnel in comparison to conventional methods of remediation of the seabed. The contaminated sediment is cleaned in situ, which eliminates the need for transport and storage (The Energy Resource Institute, 2014). Laboratory tests and experiments carried out on land indicate that a correctly conducted bioremediation procedure can lead to a reduction of sediment toxicity through a complete degradation and elimination of organic contaminants (NRC, 1997).

Limitations

The main limitation of the bioremediation method is the long time required for the biological degradation process, especially in the waters at our latitude. This method has been used many times on land, but experience in the marine environment is still lacking. The introduction of nutrients and oxidising substances in the marine environment is complicated and may cause a release of contaminants (NRC, 1997).

This method must be specially adapted to each contaminated zone. In addition, long term monitoring of the effectiveness of naturally present bacteria in degrading the fuel contaminating the area and an assessment of the availability of nutrients affecting the rate of degradation is needed. The selection of suitable microbes, able to degrade these contaminants is needed for a specific group of hydrocarbons. It is difficult to ensure adequate nutrient levels for microorganisms degrading contaminants (U.S. Congress OTA, 1991; Swannell et al., 1996; Radermacher).

The final fate of contaminants after bioremediation is uncertain. The residues of the microbiological degradation are usually harmless, but it is not certain whether toxic products may develop in some cases. Therefore, it is important to conduct laboratory tests before implementing this method (NRC, 1997).

In the case of, the meth the S/S Stuttgart wreck, this method can probably be considered as useful, but its effectiveness in solving the problem is not well documented. The main concerns are:

- high costs of raw materials (a factor causing biological activation of bacteria responsible for effective bioremediation),
- high cost of the operation due to the need to construct adequate equipment and the conversion of vessel(s) used for sediment treatment as well as the still undefined, but probably high cost of implementing the technology for bioremediation,
- high cost due to repeated bioremediation process (application of the substance into the sediment) and long-term monitoring,
- unspecified environmental impact and, consequently, unknown effectiveness of this method in the case of contamination with fuel coming from hydrogenation of coal in the gasification process (such fuel was on the Stuttgart ship),
- high risk of the lack of a positive impact in the case of the analysed wreck (S/S Stuttgart) – it requires long-term micro and later semi-industrial research. The requirement for high-water (and sea bottom) temperature of approx. 15°C in the place where bioremediation is applied cannot be met for the Stuttgart wreck, as the bottom water temperature ranges from 4°C to 6°C all year round,
- the advantage is the low risk of secondary contamination of the seabed and water during the process aimed at controlling the spillage,
- lack of long-term environmental impact, based on the analysis of literature, not confirmed in large-scale projects,
- in most of the described cases, the reduction time of contaminants is short, but according to some sources, in some cases the effectiveness is extremely low,
- to date, this method of reducing oil contamination of the seabed has been successfully implemented on a very small scale and nowhere in the world has this solution been applied on such a large scale.

5.6 **Removal of contaminated sediment by dredging**

Removal of fuel and contaminated sediments by dredging is the most common method among the *ex situ* methods. This method differs from conventional dredging carried out for navigational purposes and is called an *environmental dredging*. Contaminated sediment is removed with special dredgers, then transported and processed outside of the place of original occurrence, reused or deposited. Removal operation usually requires the use of supporting technologies (U.S. EPA, 2004). Dredgers remove a certain amount of water together with the sediment, then it is dewatered on land and the recovered water is usually discharged back into the sea. Heavily contaminated sediments need additional treatment before depositing and are often subject to a stabilisation process. In some cases, fuel can be remediated by separating water and sediment through the decantation process (Fitzpatrick et al., 2013).

When planning dredging, a number of factors should be taken into account, such as: depth, volume of the material for extraction, sediment characteristics, the risk of disturbing protected habitats and presence of waste at the bottom. This method is the most effective when there is a need to remove contaminated sediments in the form of *hot spots* and to protect an area against spreading of contaminants. It is also recommended in a case when the secondary residual contamination, resulting from the release of contaminants in water column at the moment of dredging, is considered less important than the need for long-term reduction of the contamination risk (ITRC, 2014). Secondary contamination as a result of dredging may be greater in the presence of boulders, small stones and buried objects. Due to the risk of significant resuspension (dispersion of contaminants) and release of contaminants during transport, there is a need to conduct monitoring during removal of contaminants (U.S. EPA, 2004). Removal of contaminated sediments is not recommended, among others, in the following cases: in the case of large areas with low concentration of contaminants, where a low risk reduction is expected; in the case of an environment with low energy (low erosion rate), where the risk of secondary contamination due to resuspension or erosion of surface sediments is low; in the case of contaminants buried under clean sediment and where there is a low risk of a release of contaminants due to extreme phenomena, e.g. storms, to the degree causing unacceptable risk, and in areas with a significant amount of waste at the bottom or areas with sensitive ecosystems (ITRC, 2014).

The ITRC (2014) and U.S. EPA (2005) papers describe in detail the environmental conditions and other factors that need to be taken into account when deciding whether to pursue a dredging strategy, describe the dredging technology, as well as the results and measures, which should be undertaken during the dredging operations and after their completion.

Types of dredgers and examples of use

There are different types of dredgers, designed for different conditions. Two basic types can be distinguished:

- **mechanical dredgers** – remove the sediment by grabbing and lifting the sediment onto the barge, where it is stored and transported ashore. A dredger of this type has a rotating crane operating the gripper in the form of a scoop, mounted on the barge, equipped with a cutting and grasping edge (Figure 42). It is effective in removing heavy, hard-packed sediment or solidified oil, in places with limited access and in areas with deposited waste, such as tree branches, tires and rubble. The method is not suitable for removing gravel, dense sand and more firm sediments, such as clay, peat and highly consolidated loams (ITRC, 2014; Tetra Tech, 2013). Usually several barges are used to collect the removed sediment and transport it ashore. Clamshell is a conventional mechanical dredger. Other types of mechanical dredges include enclosed bucket dipper, bucket ladder, grab ladder, articulated bucket (Castle et al., 1995; U.S. EPA, 2005). A mechanical dredger was used after the accident of the *Erika* tanker, to remove heavily oiled bottom sediments (IMO, 2011). Renholds (1998) gives examples of not entirely effective use of the clamshell dredger (Figure 42), e.g. in the case of the Hamilton Harbour, where all contaminated sediments could not be removed or the Zierikzee Harbour, where more contamination of the sediment was observed after dredging than before the operation. In the case of *Dofasco Boatslip* muddy sediments came from under the dredger, resulting in mixing of clean and contaminated sediments.

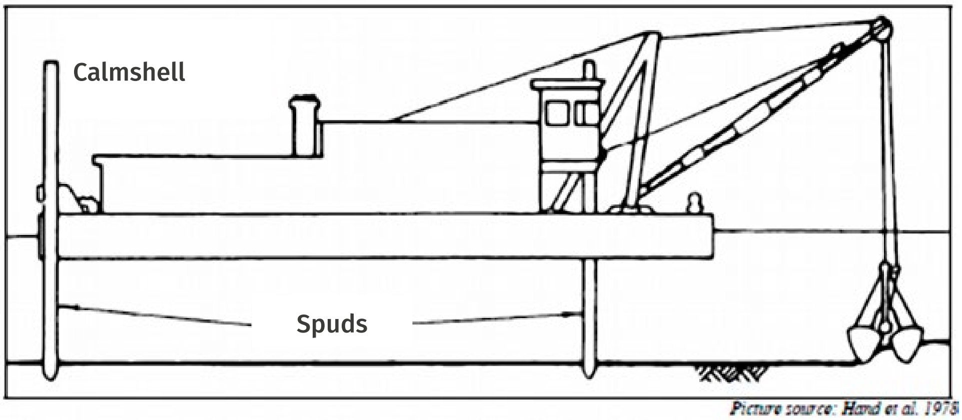

Figure 42. Mechanical clamshell dredger (Source: IMO, 2011)

- **hydraulic or suction dredgers** – cut and mix the sediments with water, so that the material can be transported through the pipeline to the land drainage system and to the disposal site. Hydraulic dredgers are composed of a dredge head and hydraulic pump (Figure 43). They can be used at great depths (even up to 100 m). Some types of hydraulic dredgers are equipped with cutting tools in order to facilitate work during dredging. However, they cause severe sediment disturbance. They remove the sediment faster than mechanical dredgers, but bring more water into the removed sediments. They are usually more effective in removing less dense sediments (with higher water content) than mechanical dredgers. This type of a dredger can only be used in calm waters. Bottom sediments are usually removed before using a hydraulic dredger, because they significantly reduce the effectiveness of hydraulic dredging (U.S. EPA, 2005, 2008). Suction dredgers were used for cleaning the area with a lower concentration of oil during the accident of the *Erika* tanker (IMO, 2011). Cutterhead is a conventional hydraulic dredger. Other types of dredgers with some modifications are swinging ladder cutterhead, horizontal auger, plain suction, hopper, special dredgers and dredgeheads and dredgers assisted by divers (U.S. EPA, 2005, 2008).

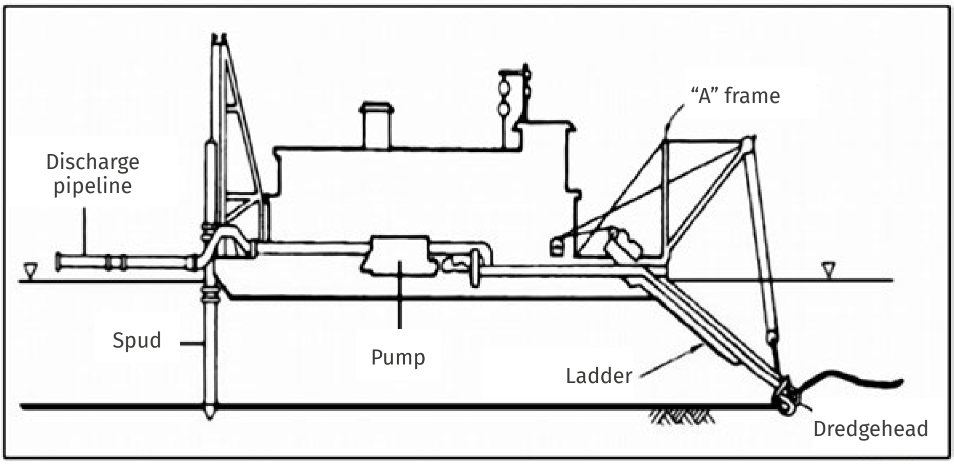

Figure 43. Hydraulic dredger (Source: U.S. ACE, 2008)

There are also **hybrid dredgers**, which are a combination of hydraulic and mechanical dredgers (Figure 44). The sediment is taken with a scoop, which enables it to preserve the natural water content and reduces the volume of sediments that require processing. It is then transported using pumps through a pipeline directly to the coast (U.S. EPA, 2005, 2008).

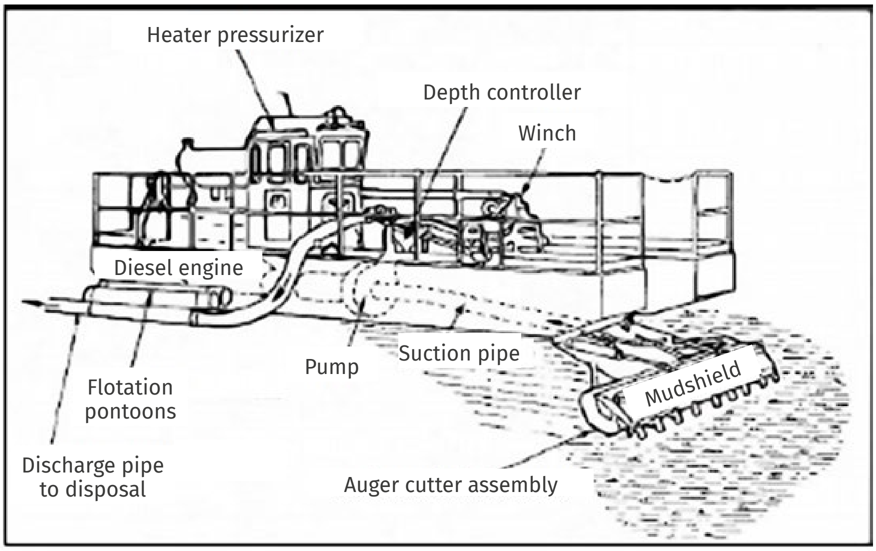

Figure 44. Mechanical hydraulic dredger (Source: IMO, 2011)

A **pneumatic dredger** is a special type of dredger, working in a similar manner to a hydraulic dredger. It uses a submersible pneumatic pump and suction pipe mounted on a crane on board (Figure 45). The sediment enters the pump through hydrostatic pressure and is pumped into surface pipelines or to the vessel using compressed air. Pneumatic pumps do not have any depth limits and can achieve a high coefficient of solid particulates in relation to water (up to 80%) with minimum turbidity. The efficiency of such a pump increases with the depth and quantity of supplied air. Compared to hydraulic dredging, the advantage of pneumatic dredging is the fact, that the pumped material does not have to be liquid but can contain up 70% of dry matter (Castle et al., 1995). Such a system was used in removing oil spill after the accident of the *Haven* ship. A ROV vehicle with a tool to cut oil into smaller pieces was also used (IMO, 2011). Pneumatic dredges were also successfully used in removing PCB contamination in the *Duwamish* river in the United States, PCB contamination in the Great Lakes in Canada and seriously contaminated sediments in the Osaka port in Japan. Examples of pneumatic dredgers include the Italian dredger *Pneuma* (used in oil spill in Duwamish) and the Japan dredger *Oozer* (Rymell, 2009; www.pneuma.it). A small pneumatic dredger, called the air lift is also mentioned in the literature (HELCOM, 2002).

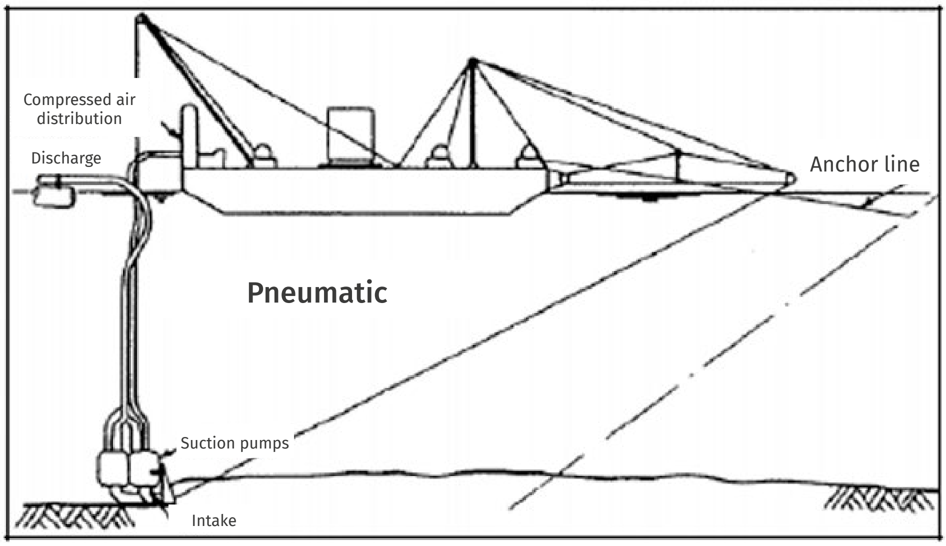

Figure 45. Pneumatic dredger (Source: IMO, 2011)

For more detailed information on dredger types, see the dredging guidelines in the publication U.S. ACE (2008). Dredgers were used to remove fuel from the bottom in many cases of oil spills. Several examples are mentioned in the publication of ITRC (2014).

Costs

Castle et al. (1995) in their study refer to the cost of labour of different types of dredgers. For a pneumatic dredger the cost ranges from 1.40 to 4.00 $ per m^3, for a mechanical clamshell dredger 2.10 $/$m^3$, and for hydraulic dredger 1.95 $/$m^3$.

The total cost of this method includes, apart from basic costs of dredging, significantly higher costs of other operations, such as storage, processing of extracted sediment, transport and landfill (NRC, 1997). In addition, the costs of supporting technologies, protecting against secondary contamination, and isolating contaminants released into the water during dredging, should be included (e.g. booms and skimmers).

According to the National Research Council, the total costs of dredging including removal and transport do not exceed 15$ to 20$ for cubic yard (19.7$ to 26.3$ per m^3). However, when using a processing technology for contaminated sediment, the cost may raise to over 100 $/$yd^3$. This has been confirmed by the costs of operations presented in the ITRC publication (2014). The costs of dredging may be reduced by using technologies for precise dredging, minimising the use of water and uncontaminated sediment (NRC, 1997).

In many cases, dredging was used in combination with other cleaning methods. Michel et al. (2005) in their publication include several examples of operations carried out on different wrecks.

Advantages

The method of removing contaminated sediment by dredging is the fastest and the most radical method of removing oil and contaminated sediment from the bottom (Fitzpatrick et al., 2013). This solution is useful in the case of vast contaminated areas, in particular in the case of oil that cannot be pumped. This method can be used in a dynamic environment (U.S. EPA, 2004).

Limitations

It is the most invasive method to remediate the bottom and has a short-term, but destructive effect on the ecosystem of benthos organisms (IMO, 2011; U.S. EPA, 2004). The release of contaminants during the operations also has a negative effect on other marine organisms. Dredging causes sediment disturbance and leaves residual contamination. It is difficult to predict the scale of residual contamination after the operation. There is also a high risk of loss of contaminants during transport (NRC, 1997). Moreover, the dredgers are not in a position to remove less than 20 cm of the thickness of bottom sediment (Rymell, 2009).

This method is one of the costliest and is more complicated than other methods. Extracted sediments and contaminants require storage, transport, processing and landfill. Due to the high water and sediment uptake together with contaminants, it is often necessary to separate these components through decantation. High logistic requirements are another restriction (Castle et al., 1995; U.S. EPA, 2004).

In the case of the contamination around the S/S Stuttgart wreck, this method cannot be considered useful for solving the problem. It is the least beneficial and possible to use method of cleaning up oil spills from the bottom sediments. The main reasons to support this position are:

- high costs of tools used to lift the contaminated sediment from the bottom, in particular when using specialised tools preventing the discharge of contaminated water and part of the sediment back to the sea,
- high cost of the operation due to the need to construct adequate equipment and the conversion of vessel(s) used for sediment treatment, as well as cleaning water from dissolved oil fractions,

- high cost of transporting contaminated sediments ashore and transhipment on land, and the need to transport sediment to the processing plant with extreme caution,
- very high cost of remediating the sediment from contaminants (e.g. by burning at high temperatures),
- high storage cost (due to huge amount) of remediated sediment on land, e.g. in toxic waste storage site (at present practically not possible due to the provisions),
- very large and long-term damage to the environment (it is the most invasive method for removal, cleaning up and storage of contaminated sediment),
- very high risk of secondary contamination of the bottom and water around the wreck during the operation aimed at remediating the oil spill.

The presented methods will not effectively remediate the threat posed by the fuel on the S/S Stuttgart wreck. Only the backfilling method places a physical barrier between the tanks and the surroundings, thus reducing the release of the contaminated substance. In the case of the S/S Stuttgart wreck, there is a reasonable suspicion (although not proven due to the lack of direct survey of the wreck) that the tanks contained an undefined amount of heavy fuel. There is no information in which tanks or what amount of fuel is still in the wreck. However, a comparison of the results of the survey carried out in 1999, with data from 2009, 2012 and 2015/16 indicates that the heavy fuel keeps on spreading, as the wreck is the only possible source of this oil, it must still be escaping from it. For complete certainty, the wreck should be checked to determine the type and quantity of the remaining fuel. A plan should then be devised for its removal.

Therefore, this section of the report will discuss methods of removing fuel from the closed space of the wreck, such as tanks and spaces filled with fuel as a result of the spill after the ship had sunk.

5.7 *Hot-tapping* and pumping fuel residues from the wreck with a ROV

In a situation when there is trapped oil in the wreck's tanks, the most effective and modern method to retrieve it involves the use of a ROV robot and *hot-tapping* technology. Hot-tapping was first carried out by divers, for example during the operation on the *Cleveco ship* (Davin, Witte, 1997) or *Mississinewa* (U.S. Navy Salvage Report, 2004). Due to the risks faced by divers, which increase with water depth, special ROV vehicles were designed to remove oil at greater depths. The technology based on a ROV operating the *hot-tapping* device was first used in the case of the oil spill from the Prestige ship, at 3500 m depth. A remote vehicle ROLS (*Remote Offloading System*) designed by FRAMO and a Hot Tapping Machine, designed by Respol, were used to retrieve oil from the tanks of sunken vessels (Figure 46). ROLS was also used on other vessels, such as *Estonia, Levoli Sun, Yuil No. 1 and Osung No 3., Bow Marine* (IMO, 2011; Michel et al., 2005).

In his study, Alfons Håkans presents the operation of oil retrieval from a wreck, using ROV and *hot-tapping* (*SS Park Victory and MS Estonia*) (Figure 47). The operation carried out by ROV robot is composed of the following steps:

- cleaning the hull before measurements and penetration,
- analysing the state of the oil tank and the access,
- measuring the thickness of the plating,
- determining the location of the frame and the access point,
- installing the valve,
- installing the *hot-tapping* device,
- connecting the ROV with the *hot-tapping* device and transfer to place of operation,

Figure 46. *Hot-tapping* device used at Prestige wreck (Source: Michel et al., 2005)

- penetrating with the *hot-tapping* device and installing a release valve in the tank,
- the hot-tapping device installs the pressure compressing valve,
- ROV checks twice the valve,
- ROV conducts a self-closing device to the release valve,
- optional devices: *Double Bottom Tool, Booster Discharge Pump Unit* and oil viscosity control system,
- retrieving oil from the wreck,
- end of the operation.

During the operation, the *hot-tapping* device (Figure 47) adheres to the hull of the wreck. It is equipped with cutting tools, used to cut an opening. The oil suction valves and pressure compressing valves are then introduced. The oil is extracted with a vacuum suction pipe to the tank floating at the surface. If the oil is too dense (due to the type and low temperature), heating equipment is introduced to the tank to increase the oil temperature and reduce its viscosity, which allows to pump it out. After retrieving the oil, the valves are closed (Michel et al., 2005; NOAA, 2013).

Taking into account the process of oil retrieval with the use of ROV and *hot-tapping* technology, the following criteria need to be defined to select appropriate equipment: water depth, sea and air condition, state and structure of the wreck, quantity of oil to be pumped out, type of oil and its proprieties (in particular its viscosity), number and location of tanks in the wreck, access to the tanks, water temperature and water currents (Michel et al., 2005).

In the case of some wrecks, especially from the war period, it is necessary to determine whether there is oil in the tanks. Since the recovery of oil from SS *Jacob Luckenbach* wreck, neutron backscatter system is used to assess the presence of oil in the wreck tanks. In 2011, the location of oil in the *Montebello* wreck, which sunk in 1941 at the depth of 274 m, was determined using the neutron backscatter system. The results of the research were approved by FOSC (*Federal On-Scene Coordinators*) (NOOA, 2013).

There is a wide variety of applications for vacuum pumps: from simple diaphragm pumps to high-volume vacuum rotary pumps. Very viscous, heavy oil or debris can block the suction pipe. In such cases, technologies that lower the viscosity of the liquid are used to support the efficiency of the process. The most common method is to heat up the tanks, using heating coils, hot water or steam. Another method is to mix the extractable liquid with a light fuel such as diesel fuel. This method was practiced on the Erika tanker. Agents may also be added to the fuel to increase its viscosity to such a level that it becomes a semi-fluid rubber, which in turn lowers the risk of leakage (NOAA, 2013; Michel et al., 2005).

Figure 47. ROV with *Hot Tapping* device produced by Alfons Håkans
(Source: Estonia and Park Victory cases info 2015-12-08 KR.pdf)

Examples of use

The method of retrieving oil from a wreck with the use of ROV and a *hot-tapping* device has been used on several occasions. For example, the operations carried out by the Finnish company, Alfons Håkans in the Baltic Sea, on the *Park Victory and M/S Estonia*, *Brita Dan and Coolaroo* wrecks (www.environment.fi). The following details the work carried out on two wrecks by Alfons Håkans (Estonia and Park Victory cases info 2015-12-08 KR.pdf):

- **The case of the Park Victory wreck**

  The oil removal operation from this 50-year old wreck was conducted over the period of 6 years. The wreck was in a poor condition and oil emissions had been detected during several years, especially in the summer months. First, the coal, lying on the wreck and blocking access to the tanks, was removed. An *air lift* pump designed by Mammoth was operated by a ROV with the assistance of divers. Then, 30 holes were drilled and the TAIFUN Vacuum Pumping System was connected. Due to the low water temperatures at the bottom, the tanks were initially heated with hot steam, water and compressed air. In total, the operation took 5.000 hours for both ships, 1.200 hours for the divers underwater and 1.700 hours for the ROV inspections. 410 tonnes of heavy oil were removed. The total cost of the operation was FIM 21.3 million.

- **The case of the M/S Estonia wreck**

  The oil removal operation began in 1996 and lasted for ten years. The ROLS system was used, together with the TAIFUN pump and the ROV robot. 4 drilling machines were used. First, light fuel was pumped out, and then heavy oil, located under the double bottom. Mechanical separation of water in a centrifugal separator was also carried out.

Costs

The total cost of oil retrieval depends on a number of factors, such as: the quantity of oil, its viscosity, the number of tanks, the depth, water and weather conditions, the structure of the wreck, its state, and the cost of gaining access to the tanks. Logistic factors are also important, such as: the availability of supplies and equipment for the operation, required response time range, work and downtime time, costs of mobilisation and demobilisation and the costs of disposing or recycling the removed oil (Hassellöv, 2007, Alfons Håkans Estonia and Park Victory cases info 2015-12-08 KR.pdf).

Tables 9 and 10 present examples of operations carried out with hot-tapping assisted by divers and by a ROV, as well as the costs.

Table 9. ***Hot-tapping* operations, assisted by divers** (based on: NOAA, 2013; McGrath, 2011)

Vessel	Retrieval year	Characteristics	Oil retrieved	Total cost	Unit cost
Princess Kathleen	2010	Heavy oil, hydrogen sulphide, depth 40 m. Poor state of the wreck (riveting)	2 620 barrels	14 million $	5 344 $/barrel (125$/gallon)
USS Mississinewa	2003	Heavy oil, small depth, Tanks easily accessible. Low complexity of the operation	42 000 barrels	4.5 million $	107 $/barrel (2.55$/gallon)
Jacob Luckenbach	2002	Heavy oil. Depth 52. Very sensitive surroundings	2 450 barrels	20 million $	8164 $/barrel (194$/gallon)
Erika	1999	Heavy oil. Wreck in two parts, at 100 and 130 m, located at a distance of 18 km	11.200 tonnes	>200 million €	18 857 €/ tonne (448,9 € /gallon)

Table 10. ***Hot-tapping* operations, assisted by a ROV** (based on: NOAA, 2013 oraz McGrath, 2011, Alfons Håkans Estonia and Park Victory cases info 2015-12-08 KR.pdf)

Vessel	Retrieval year	Characteristics	Oil retrieved	Total cost	Unit cost
Prestige	2004	Heavy oil Depth 3650 m	91.000 barrels	132,6 million $	1 460 $/ barrel
Park Victory	1994-2000	Heavy oil Cold water Depth 20-40 m	410 m^3 of heavy oil	21,3 FIM (15,5 million PLN)	9,14 €/l 9140 €/m^3
M/S Estonia	1996-2006	Heavy and light oil Depth 60-80 m	418 m^3 (including 302 m^3 of different types of oil)	No data	No data
Osung No.3 i Yuil No.1	2001	Heavy oil Depth 69 m Sensitive ecosystem	4 600 barrel	13 million $	2 826 $/ barrel

Advantages

The pumping method with the use of a ROV and a *hot-tapping* device permits the removal of oil from wreck's tanks more precisely than old generation pumping systems. The use of the ROV for removing the oil enables faster operations and at greater depths, without breaks needed for personnel rotations, as is the case while using pumps operated by divers. Moreover, the use of a ROV allows operations to be carried out in more unfavourable weather conditions. The method significantly reduces the risk of oil leakage and dispersion during pumping and allows the oil tanks to be completely emptied (Alcaro L. et al., 2007; Michel et al., 2005; NOAA, 2013).

Limitations

The method has limitations in terms of the amount of oil retrieved and the retrieval time. The retrieval process is slow. The method is very expensive and complicated in terms of the logistics. It requires experienced personnel and advanced electronic equipment, as well as a large platform to support the equipment. The extracted oil requires transport and must be disposed of or recycled. Breaks due to the unfavourable weather conditions are inevitable (Alcaro L. et al., 2007; Michel et al., 2005; NOAA, 2013).

In the case of the S/S Stuttgart wreck this method can be useful as a process supporting the solution of the problem. It can be considered as a useful and environmentally friendly method for quick retrieval of oil from wrecks. Engagement of divers or use of a ROV to remove the oil may be necessary in the discussed Stuttgart case, if the presence of oil in the tanks is confirmed. There are several issues, that need to be taken into account and solved:

- the need to "dredge" (remove the sediment around the bottom part of the wreck) to get access to bottom tanks. This will generate enormous costs, due to the time-consuming nature of this process, as well as the complexity of the work carried out with specialised equipment and by divers,
- high costs of equipment used to clean the tanks,
- a large amount of resources needed (both people and equipment) from the highest price range,
- the need to provide transportation and disposal/recycling of recovered oil,
- advantage: very low and reparable environmental damages (it is the least invasive method of removing oil from wrecks),
- low risk of secondary contamination of the sea bottom and water in the vicinity of the wreck during the operation.

5.8 Auxiliary supporting technologies for oil removal

In addition to the above mentioned methods for removing oil from the sea bottom or from wrecks, auxiliary technologies aimed at stopping or removing the oil drifting in the water column or at the water surface are used. Below are those that can be applied in the case of the S/S Stuttgart wreck and which can be used as protective measures, when removing oil from the sea bottom as well as for reducing the pollution spread, in the case of an accidental oil release into the water during the retrieval operations (IMO, 2005).

5.8.1 Booms

Booms are elastic barriers made of flotations devices, a sub-surface skirt and ballast. They surround floating oil to prevent its spread over the water surface and divert its stream. They can be towed between two vessels in the open sea (Figure 48) or located in front of the shore, to protect certain areas against pollution. There are different types of booms, differing in construction and use, namely: flexible, pneumatic and absorbing (www.sebekfireman.host247.pl/straz/wiedza/n18.htm). Oil collected in the boom may be removed using skimmers or special vacuum pumps (IMO, 2005; ITOPF, 2014; Marine Pollution

Clean-up Manual, 2013; Preston i in., 1997). An example of such technology is a turbidity curtain produced by ELASTEC (www.elastec.com/turbiditycurtains/).

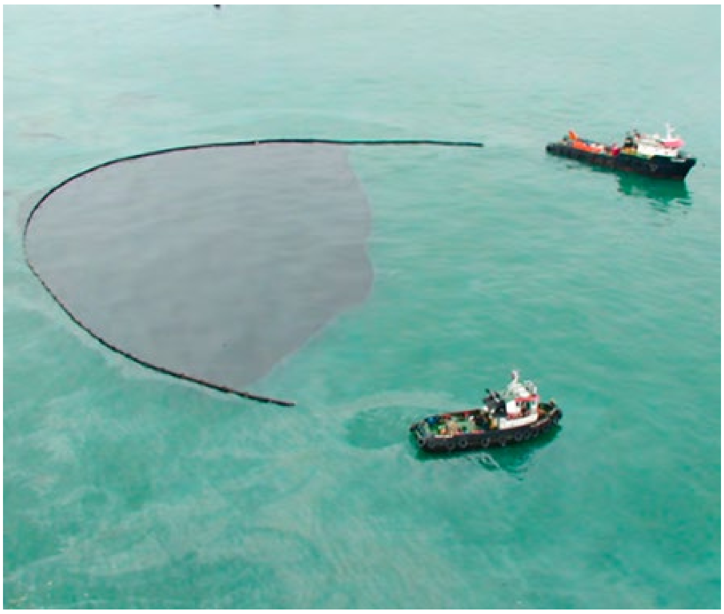

Figure 48. A boom in open waters (Source: ITOPF, 2014)

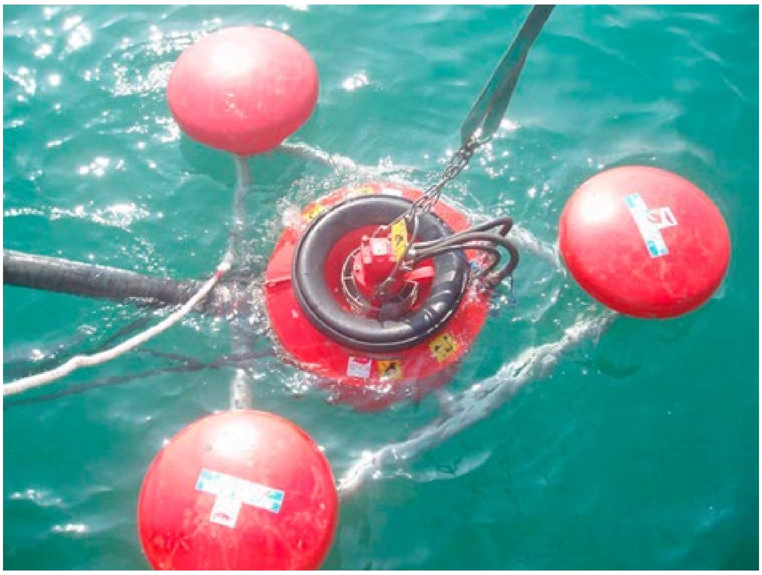

Figure 49. Skimmer (Source: Marine Pollution Clean-up Manual, 2013)

5.8.2 Skimmers

Skimmers are used to recover oil from the water surface. The scope and method of this operation depends on the oil layer, viscosity and sea conditions. The oil is collected into a tank and then discharged to the collector with a hose. Skimmers are most effective when combined with booms. There are different types of skimmers, namely: pump, desiccant, adhesive and screw-type (IMO, 2005; ITOPF, 2014; Marine Pollution Clean-up Manual, 2013; Preston et al., 1997).

5.8.3 Other pumps

EDDY pump – is a dredging pump used for oils with high viscosity, optimised for extracting solids in suspension, sand and thicker sediments. It treats high viscosity oil as solids (www. eddypump.com; IMO, 2011).

OSBORS (*Oil Stop Bottom Oil Recovery System*) produced by the American Pollution Control Corporation (AMPOL), is a remote-controlled dredger (Figure 50), designed to recover oil from the seabed. It is equipped with a centrifugal pump and movable suction hose (IMO, 2011; NOAA, 2013).

Manual pumps – are diver-operated pumps that enable the removal of liquid oil from the water surface or submerged in water. The pump is equipped with a suction head and is connected to the ship with a long cable through which the removed fuel is transported (Hansen, 2011; IMO, 2011).

Figure 50. OSBORS unit used to retrieve oil from the bottom
(Source: NOAA, 2013)

5.8.4 Oil, water and sediment separators

Oil collected from the water surface may require separation from the water. For this purpose, oil and water sorption can be carried out in a special decantation system installed on a barge. Water is discharged back into the sea and the separated oil is burned on the site or transported to the landfill (Hansen, 2011; Fitzpatrick, M. et al., 2013).

5.8.5 Other technologies

In addition to the above mentioned technologies, depending on the measure used, the conditions at sea and the type of fuel, the following technologies are also used in oil spill response:

- dispersants (dispersing the oil spilled on water surface),
- sorbents, i.e. oil- absorbing substances or materials, which may be of organic (e.g. peat) or inorganic origin (e.g. volcanic ash, clay),
- gelling agents and other substances that change the physical state of the oil to facilitate its extraction,
- mobile and floating tanks, towed tanks and tanks installed on board a vessel or barge (allowing temporary storage of contaminants) (www.epa.gov; Marine Pollution Clean-up Manual, 2013; NOAA, 2013; Walker, 2003).

5.9 Comparison of methods and proposals for remediation of contamination

5.9.1 General costs

Each maritime accident that requires the removal of the remains of a toxic cargo or fuel from the ship's tanks is different and therefore it is difficult to accurately estimate the costs of such an operation beforehand. Both, the implementation of the operation and its costs may significantly differ from the initially planned ones, especially if oil is removed from an old wreck and there is no information on how much oil is in the tanks, how it is distributed and what is the access to the tanks.

Other important factors of cost estimation include: the depth of the wreck; the available technology and available equipment; the distance from the wreck to the operation base, where vessels used for remediation can stop; and even the time of the year, weather conditions, water and air temperature are important and should be considered. Therefore, cost estimation must take into account a number of elements that cannot be influenced in any way. The guide of the American Environmental Protection Agency (EPA) discusses in detail all the cost elements, that need to be taken into account in estimating the planned remedial operation documented during a feasibility study (U.S. EPA, 2000). The main elements include: mobilisation, demobilisation, monitoring (including analyses and sampling), collection and separation of water, removal of sediment, preparation of the capping material, in-situ operations, ex-situ operations, transport and storage of contaminated sediment and elements related to professional technical services, design, planning, management and inspections. The NOAA publication on the risk assessment of potentially polluting wrecks (2013) lists all the factors that affect the assessment and removal of the oil. These factors include:

- type of oil and its properties (primarily viscosity);
- oil volume;
- water depth;
- bottom currents;
- sea state (e.g. protected waters, open sea);
- weather conditions;
- resources at risk (sensitive habitats);
- distance from the shore, distance from mobilisation place, logistical support;
- vessel configuration (e.g. tank locations, ventilation and piping systems, location of tank baffles, general construction);
- vessel construction (e.g. plate thickness, riveting, welding);
- vessel age (date of construction, modernisations, sinking);
- wreck condition (e.g. broken sections, corrosion);
- wreck orientation (e.g. upright, upside down);
- safety factors (e.g. presence of munitions, hazardous materials, derelict fishing gears);
- other cargo (may still block access to tanks and take up space);
- historical/cultural concerns (historical significance, war grave).

The NOAA publication (2013) presents the costs of oil removal, estimated on the basis of past oil operations of this type (as of 2012). The following factors were taken into account, when calculating the costs: water type, depth, oil viscosity, water temperature, wreck condition and vessel characteristics. Taking into account these factors, the S/S Stuttgart wreck can be classified as "complex" or "highly complex" operation (the cost range for these groups of operations is estimated respectively at: USD 5-20 million and USD 20-100 million.

Table 11. **Assessing factors influencing the costs of oil removal operations** (as of 2012)

Complexity of operation	Waters	Depth metres/ feet	Oil viscosity	Water temperature	Wreck condition	Vessel factors	Distance from mobilisation point	Cost range
		◄───	◄───	───►	◄───	───►		
Simple	Protected	65	Low	High	Good	Not very old. Optimal construction. Not very damaged Thick plating. Low location sensitivity	Local	$ 1-5 M
Moderate	Problems with weather or sea condition	65-164	Medium	Moderate	Medium	Not very old. Stable structure. Not very damaged. Thick plating of the hull. Low location sensitivity	Regional	$ 2-7 M
Complex	Open	164-820	High	Low	Weak	Old. Multiple structure damage. High location sensitivity	Distant	$ 5-20+ M
Highly complex	Open	>820	High	Very low	Very weak	Very old. Poor structure. Severely damaged. Covered with corroded plating, Highest location sensitivity	Distant	$ 20-100+ M

◄───► Interrelated factors

One of the highest costs to consider are the costs of staff and equipment, used during the cleaning operations. In marine rescue operations, the staff, the rescue equipment and service costs (including oil removal from wrecks) are calculated according to the tariffs from the SCOPIC clause (i.e. *Special Compensation P&I Clause*) (www.lloyds.com). The costs of services and equipment are contained (as of 2014) in the tables 12 and 13.

Table 12. **Daily staff rates**

Personnel	US $
Office administration, including communications	1,361
Salvage Master	2,029
Naval Architect or Salvage Officer/Engineer	1,692
Assistant Salvage Officer/Engineer	1,356
Diving Supervisor	1,356
HSE qualified diver or his equivalent but excluding saturation or mixed gas drivers	1,217
Salvage Foreman	1,014
Riggers, Fitters, Equipment Operators	812
Specialist Advisors – Fire Fighters, Chemicals, Pollution Control	1,361

Table 13. **Costs of equipment (cost per one day of rental/work)**

Portable salvage equipment	US $
Hot Tap Machine, including support equipment	1,351
Air Lift 8”	405
Oil Boom, 48”, per 10 metres	263
Pumping Equipment Air 3 „Hydraulic 8”	117 1,351
Air Hose 2”	11

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CHAPTER 6: SUMMARY

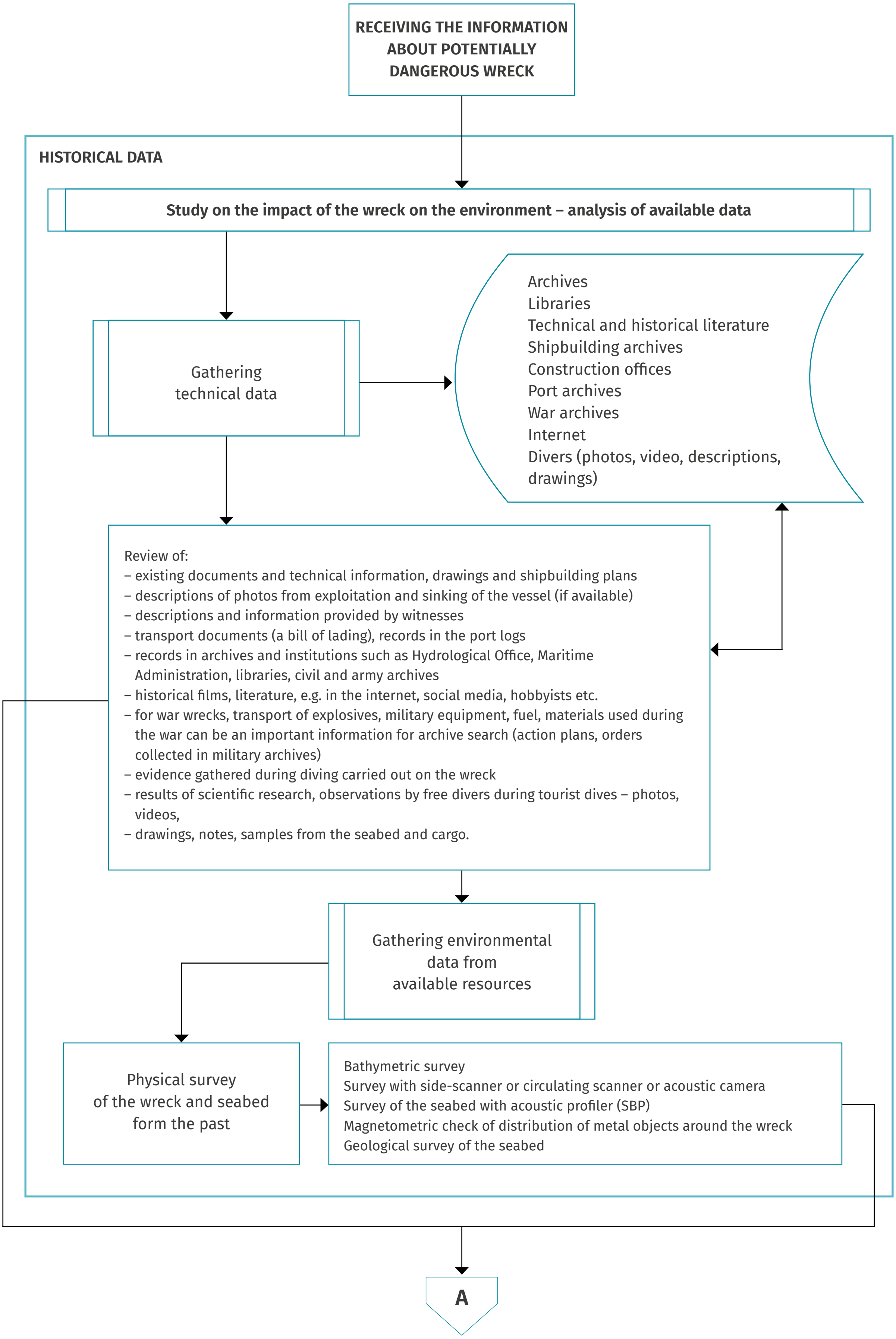
Determining the procedure to be followed when investigating the risks posed by wrecks to the environment and their mitigation, is one of the important tasks of both scientific institutions, dealing with the marine environment, and management bodies, responsible for marine areas, i.e. the maritime administration at all levels.

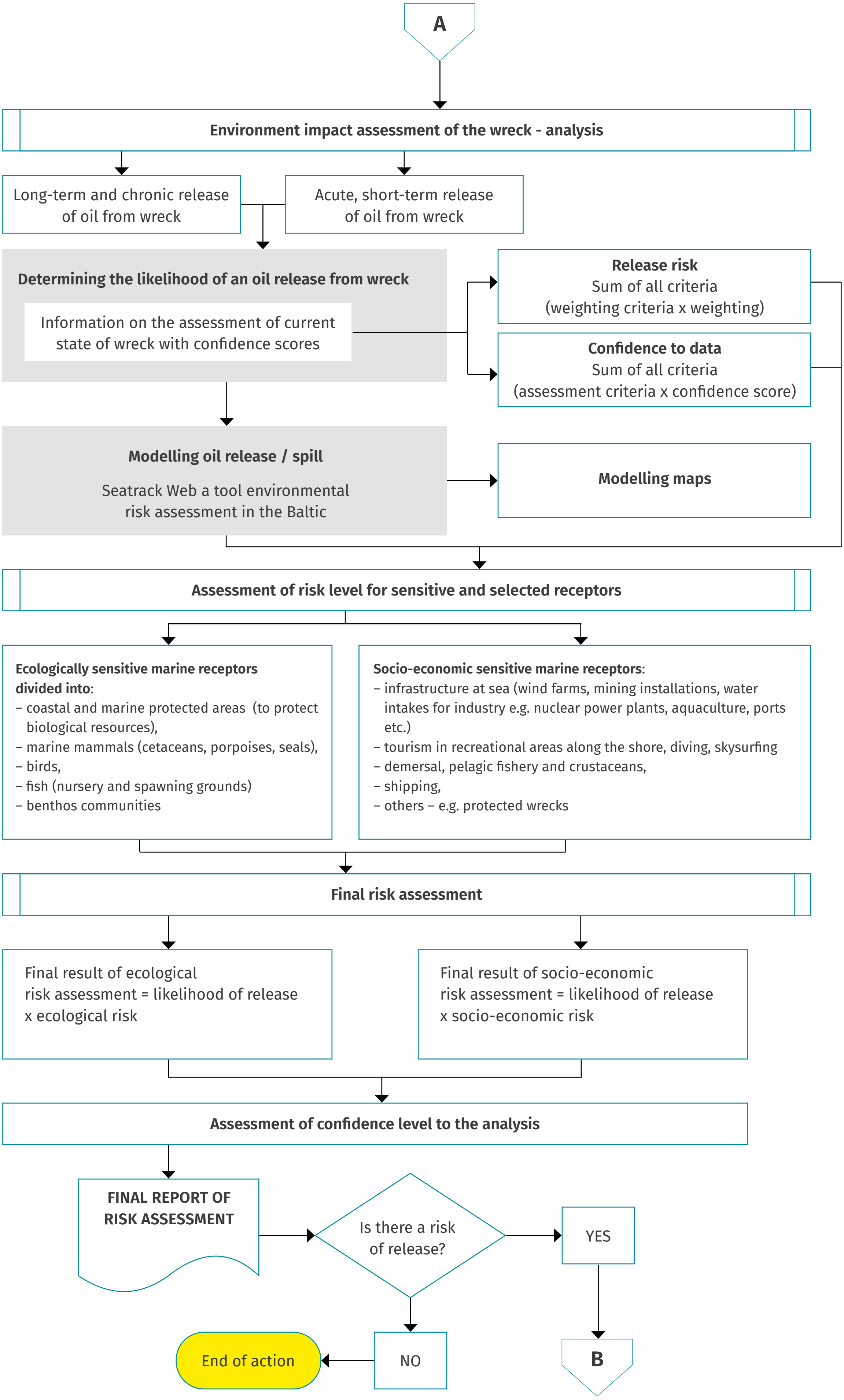
The proposals presented in this study show what should be done, when and how, to assess the risk of oil release and/or other hazardous substances from wrecks lying on the seabed. The indicated practices constitute one of many possible ways to carry out the operations aimed at assessing the risk of release, of which we de facto know very little before the assessment. The presented algorithm permits us to plan subsequent steps in the investigation and remediation process. Further decisions on whether additional measurements and clean-up operations are necessary need to be made. The proposed scheme includes all the components of the decision-making process, described in detail in the previous chapters.

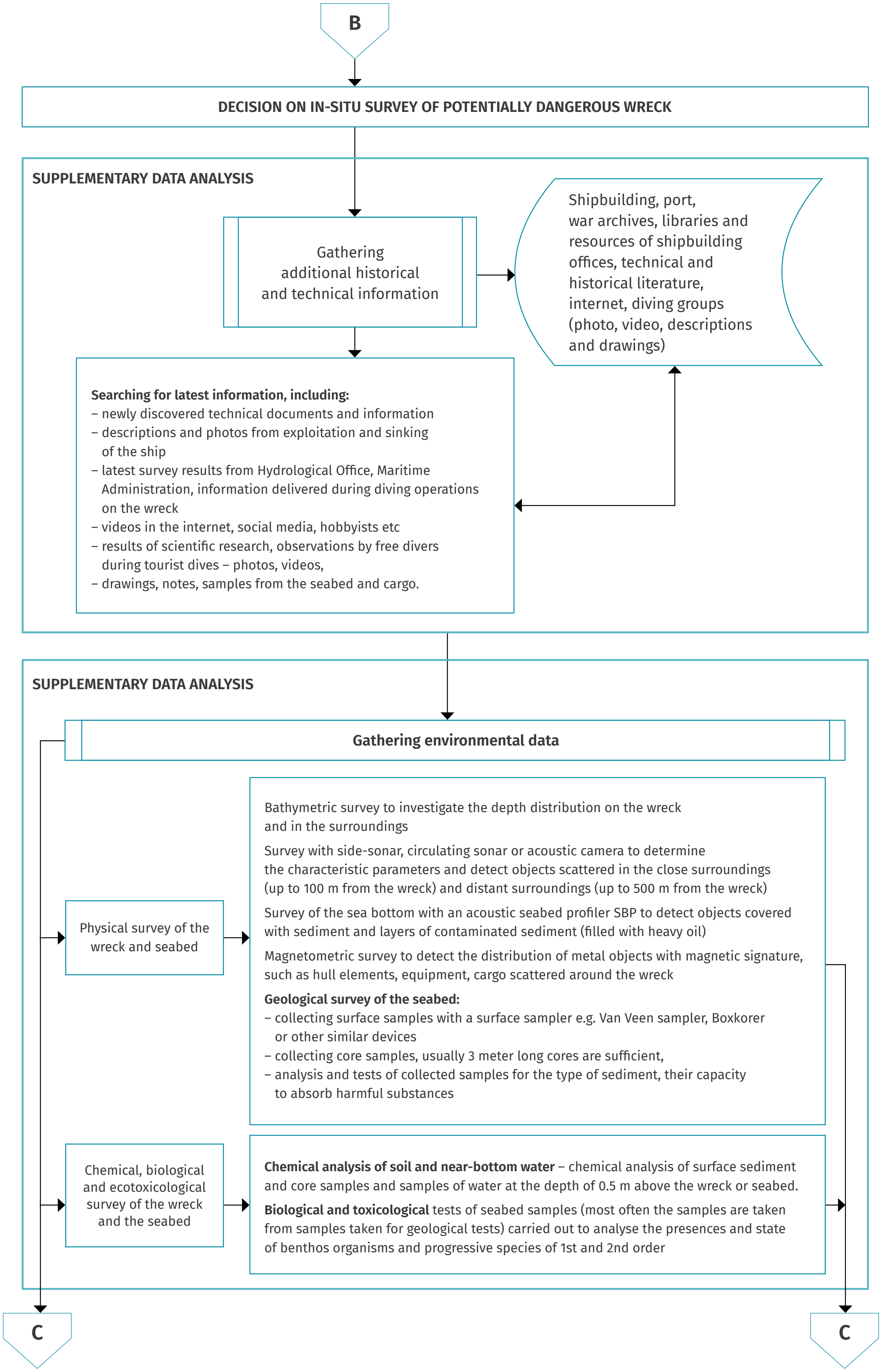
The proposed solution constitutes only one of the many possible options. With regard to the procedures discussed in the previous chapters, the scheme has been generalised to facilitate all the steps needed to obtain clear, reliable knowledge in the assessment of the level of risk posed by a wreck and its classification as dangerous or moderately dangerous. The procedure enables entry or exit from the process at any stage and therefore is universal.

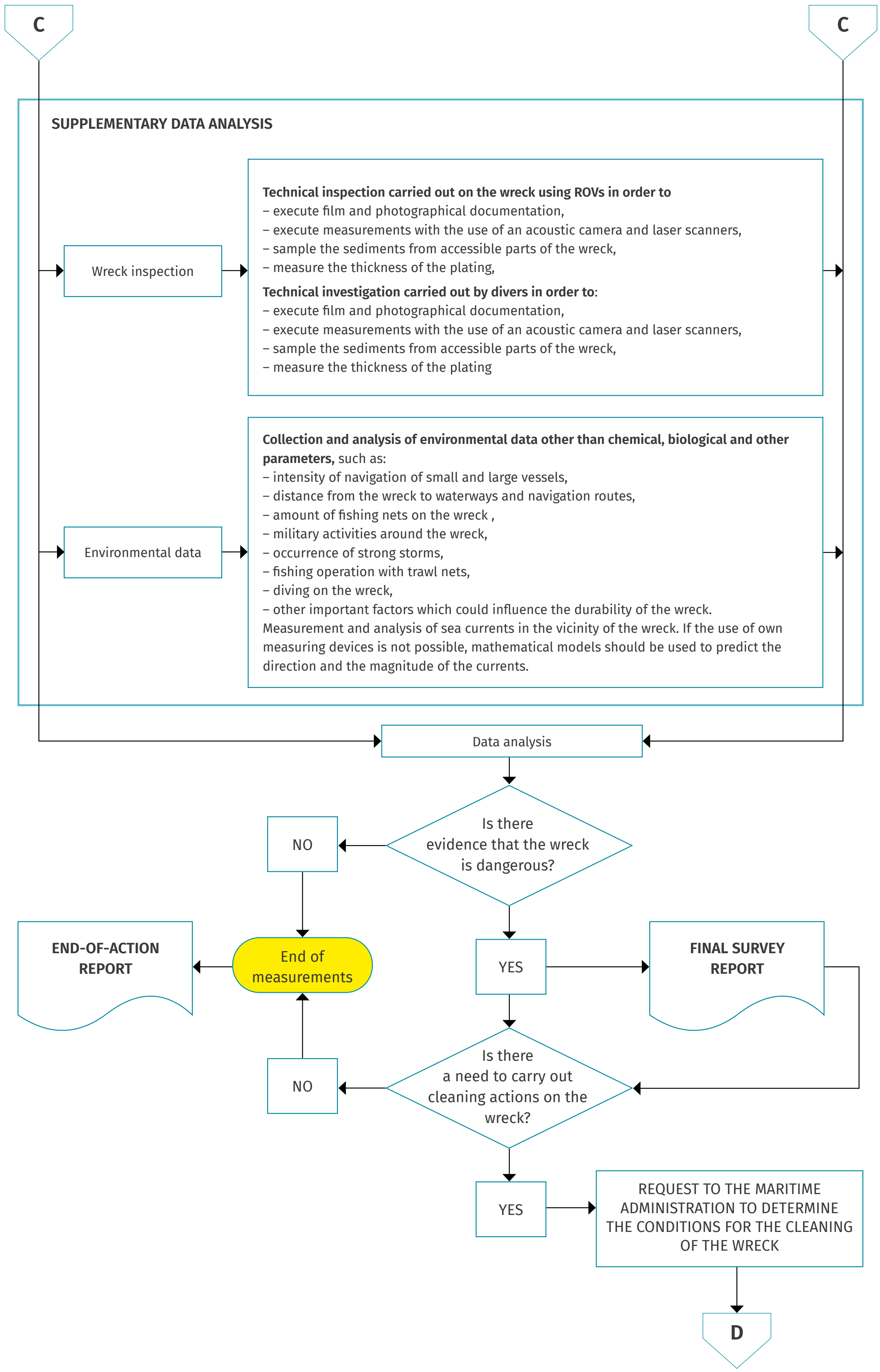
In relation to the quoted wreck assessment methods used in other countries, the proposed procedure uses the elements of the best functioning systems (i.e. in Great Britain and Sweden). However, is has been adapted to the local conditions of the Southern Baltic, the availability of tools and resources, e.g. micro and macro-scale modelling systems. The procedure provides a structured and cost-effective pathway for managing a wreck – from initial risk assessment, through detailed on-site investigation, to full environmental remediation.

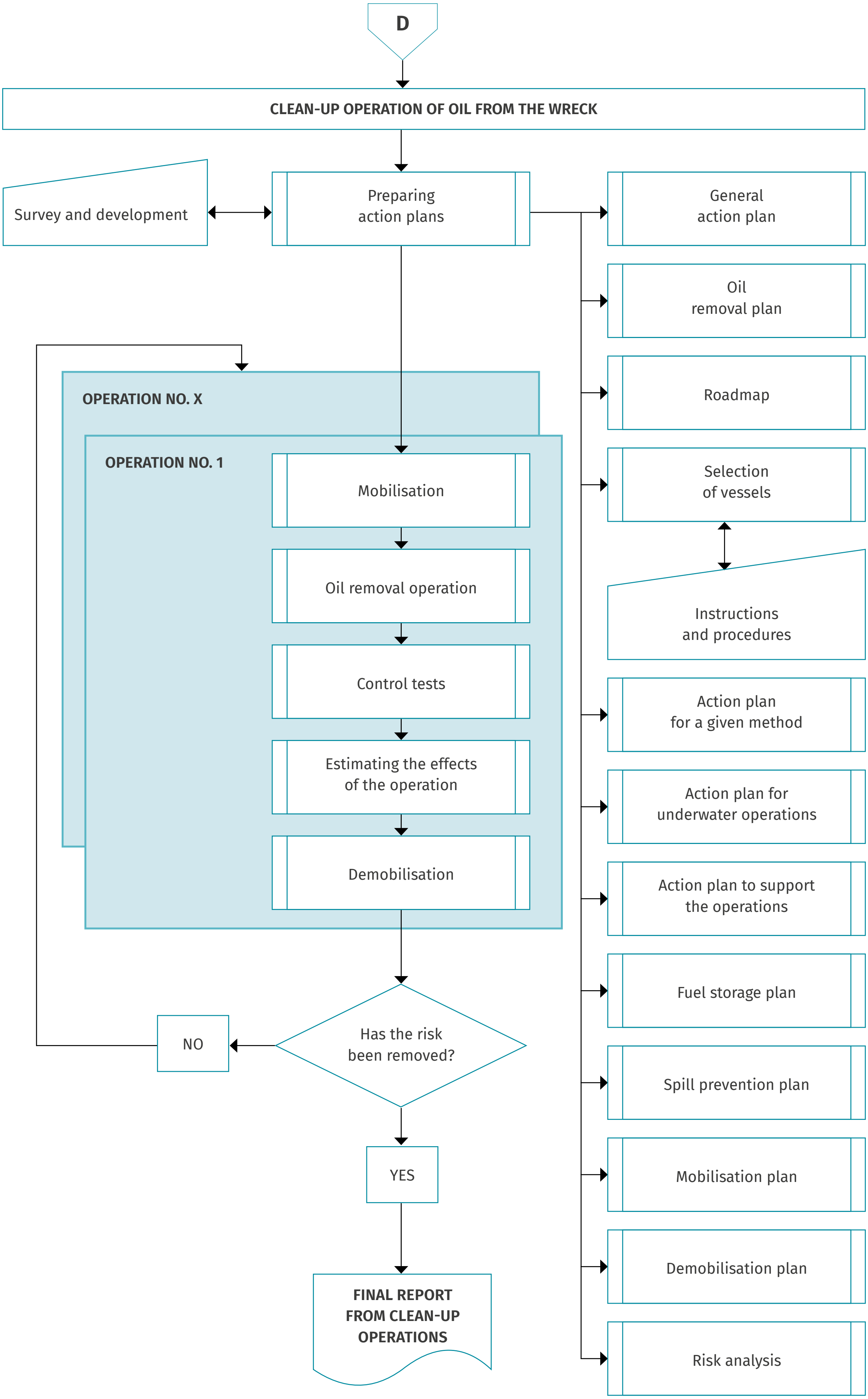
Algorithm 2. **Steps taken from the detection of the wreck, its identification, estimation of risks until the wreck is cleaned of fuel**




A
Environment impact assessment of the wreck - analysis
Long-term and chronic release of oil from wreck
Acute, short-term release of oil from wreck
Determining the likelihood of an oil release from wreck
Information on the assessment of current state of wreck with confidence scores
Release risk
Sum of all criteria
(weighting criteria x weighting)
Confidence to data
Sum of all criteria
(assessment criteria x confidence score)
Modelling oil release / spill
Seatrack Web a tool environmental risk assessment in the Baltic
Modelling maps
Assessment of risk level for sensitive and selected receptors
Ecologically sensitive marine receptors divided into:
– coastal and marine protected areas (to protect biological resources),
– marine mammals (cetaceans, porpoises, seals),
– birds,
– fish (nursery and spawning grounds)
– benthos communities
Socio-economic sensitive marine receptors:
– infrastructure at sea (wind farms, mining installations, water intakes for industry e.g. nuclear power plants, aquaculture, ports etc.)
– tourism in recreational areas along the shore, diving, skysurfing
– demersal, pelagic fishery and crustaceans,
– shipping,
– others – e.g. protected wrecks
Final risk assessment
Final result of ecological risk assessment = likelihood of release x ecological risk
Final result of socio-economic risk assessment = likelihood of release x socio-economic risk
Assessment of confidence level to the analysis
FINAL REPORT OF RISK ASSESSMENT
Is there a risk of release?
YES
NO
End of action
B


B
DECISION ON IN-SITU SURVEY OF POTENTIALLY DANGEROUS WRECK
SUPPLEMENTARY DATA ANALYSIS
Gathering additional historical and technical information
Shipbuilding, port, war archives, libraries and resources of shipbuilding offices, technical and historical literature, internet, diving groups (photo, video, descriptions and drawings)
Searching for latest information, including:
– newly discovered technical documents and information
– descriptions and photos from exploitation and sinking of the ship
– latest survey results from Hydrological Office, Maritime Administration, information delivered during diving operations on the wreck
– videos in the internet, social media, hobbyists etc
– results of scientific research, observations by free divers during tourist dives – photos, videos,
– drawings, notes, samples from the seabed and cargo.
SUPPLEMENTARY DATA ANALYSIS
Gathering environmental data
Physical survey of the wreck and seabed
Bathymetric survey to investigate the depth distribution on the wreck and in the surroundings
Survey with side-sonar, circulating sonar or acoustic camera to determine the characteristic parameters and detect objects scattered in the close surroundings (up to 100 m from the wreck) and distant surroundings (up to 500 m from the wreck)
Survey of the sea bottom with an acoustic seabed profiler SBP to detect objects covered with sediment and layers of contaminated sediment (filled with heavy oil)
Magnetometric survey to detect the distribution of metal objects with magnetic signature, such as hull elements, equipment, cargo scattered around the wreck
Geological survey of the seabed:
– collecting surface samples with a surface sampler e.g. Van Veen sampler, Boxkorer or other similar devices
– collecting core samples, usually 3 meter long cores are sufficient,
– analysis and tests of collected samples for the type of sediment, their capacity to absorb harmful substances
Chemical, biological and ecotoxicological survey of the wreck and the seabed
Chemical analysis of soil and near-bottom water – chemical analysis of surface sediment and core samples and samples of water at the depth of 0.5 m above the wreck or seabed.
Biological and toxicological tests of seabed samples (most often the samples are taken from samples taken for geological tests) carried out to analyse the presences and state of benthos organisms and progressive species of 1st and 2nd order
C
C


C
C
SUPPLEMENTARY DATA ANALYSIS
Wreck inspection
Technical inspection carried out on the wreck using ROVs in order to
– execute film and photographical documentation,
– execute measurements with the use of an acoustic camera and laser scanners,
– sample the sediments from accessible parts of the wreck,
– measure the thickness of the plating,
Technical investigation carried out by divers in order to:
– execute film and photographical documentation,
– execute measurements with the use of an acoustic camera and laser scanners,
– sample the sediments from accessible parts of the wreck,
– measure the thickness of the plating
Environmental data
Collection and analysis of environmental data other than chemical, biological and other parameters, such as:
– intensity of navigation of small and large vessels,
– distance from the wreck to waterways and navigation routes,
– amount of fishing nets on the wreck ,
– military activities around the wreck,
– occurrence of strong storms,
– fishing operation with trawl nets,
– diving on the wreck,
– other important factors which could influence the durability of the wreck.
Measurement and analysis of sea currents in the vicinity of the wreck. If the use of own measuring devices is not possible, mathematical models should be used to predict the direction and the magnitude of the currents.
Data analysis
Is there evidence that the wreck is dangerous?
NO
YES
End of measurements
END-OF-ACTION REPORT
FINAL SURVEY REPORT
Is there a need to carry out cleaning actions on the wreck?
NO
YES
REQUEST TO THE MARITIME ADMINISTRATION TO DETERMINE THE CONDITIONS FOR THE CLEANING OF THE WRECK
D


D
CLEAN-UP OPERATION OF OIL FROM THE WRECK
Survey and development
Preparing action plans
General action plan
Oil removal plan
Roadmap
Selection of vessels
Instructions and procedures
Action plan for a given method
Action plan for underwater operations
Action plan to support the operations
Fuel storage plan
Spill prevention plan
Mobilisation plan
Demobilisation plan
Risk analysis
OPERATION NO. X
OPERATION NO. 1
Mobilisation
Oil removal operation
Control tests
Estimating the effects of the operation
Demobilisation
Has the risk been removed?
NO
YES
FINAL REPORT FROM CLEAN-UP OPERATIONS

JANUARY 2021

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