THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Environmental risk assessment of shipwrecks
– Model development and application

HANNA LANDQUIST

The Department of Shipping and Marine Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
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The Department of Shipping and Marine Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
SE-412 96 Gothenburg
Sweden
Phone +46 (0)31-772 1000
www.chalmers.se

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ABSTRACT

Potentially polluting shipwrecks containing oil or other hazardous substances pose a threat to the marine environment. This is a global problem and many shipwrecks stem from the Second World War having been deteriorating on the sea floor since then. Only in Swedish waters more than 300 wrecks are estimated to pose an environmental threat. Together, these wrecks are estimated to contain between 1,000 and 15,000 tonnes of bunker oil. Every shipwreck poses a unique case depending on, for example, the type of vessel, cause of sinking, and environmental preconditions. This implies that the problem is complex and also that there are many uncertainties involved.

It is not feasible to remediate all shipwrecks due to large costs, but a proactive approach would reduce the need for and high costs of reactive response in case of a discharge. Until now, there were no comprehensive probabilistic method for assessing the environmental risk posed by shipwrecks in order to provide necessary support to decision-makers.

In order to prioritise and effectively use resources, proper decision support is needed. Risk assessments and the overall process of risk management are important means to provide such decision support. The purpose of this thesis has therefore been to develop, apply and evaluate a model for comprehensive risk assessment of potentially polluting shipwrecks. A comparison of current methods for risk assessment of shipwrecks was performed in order to identify development needs. Based on the comparison, a generic framework for risk management of shipwrecks was suggested. Furthermore, a method for estimating the probability of discharge of hazardous substances was developed, using a probabilistic fault tree method. The method makes it possible to consider possible activities that may damage the wreck as well as physical and environmental conditions affecting the wreck. An approach for consequence assessment of discharges from shipwrecks, consisting of an aggregation of methods was also developed within this thesis work.

The generic framework for risk management of shipwrecks clearly shows the important steps required and how they are linked. It also emphasizes the need of proper assessments to facilitate prioritisation of shipwrecks and an efficient resource allocation for these environmental threats. The result is a probabilistic and comprehensive model for risk assessment of shipwrecks including possibilities to cope with the vast uncertainties involved in shipwreck risk assessment.

Keywords: environmental risk assessment, shipwreck, fault tree analysis, decision support, Bayesian updating

List of papers

The thesis is based on the work presented in the following papers, referred to in the text by Roman numerals:

I. **Landquist, H.,** Hassellöv, I.-M., Rosén, L., Lindgren, J.F. and Dahllöf, I. (2013). Evaluating the needs of risk assessment methods of potentially polluting shipwrecks. *Journal of Environmental Management*, 119, 85-92.

II. **Landquist, H.,** Rosén, L., Norberg, T., Lindhe, A., Hassellöv, I.-M. and Lindgren, J.F. (2014). A fault tree model to assess probability of contaminant discharge from shipwrecks. Marine Pollution Bulletin, 88, 239-248.

III. **Landquist, H.,** Rosén, L., Lindhe, A., Norrman, J., Norberg, T., Hassellöv, I.M. & Lindgren, J.F. (2016). Expert elicitation for deriving input data for probabilistic risk assessment of shipwrecks. Manuscript for submission to *Journal of Environmental Management.*

IV. **Landquist, H.,** Rosén, L., Lindhe, A., Norberg, T., & Hassellöv, I.M. (2016). Bayesian updating in a fault tree model for shipwreck risk assessment. Manuscript for submission to *Science of the Total Environment.*

V. **Landquist, H.,** Rosén, L., Lindhe, A., Hassellöv, I.M. (2016). VRAKA – A probabilistic risk assessment method for potentially polluting shipwrecks. *Frontiers in Environmental Science, 4.*

Division of work between the authors

In Paper I, all the authors participated in stating the aim and scope and took active part in performing the work. Rosén outlined the framework for risk management of shipwrecks. Landquist performed the comparison and evaluation of methods for risk assessment of shipwrecks and was the main author of the paper.

All the authors contributed when the aim and scope of Paper II and IV were defined. Landquist, Rosén, Lindhe, Norberg, and Hassellöv developed the fault tree model. Norberg was the main developer of the mathematical foundation which was also based on discussions in the group. Lindhe and Rosén contributed largely to the theoretical description of the fault tree model. Landquist performed the simulations and was the main author.

The scope and aim of Paper III was developed by all authors. Landquist, Rosén, Norberg, Lindhe and Hassellöv developed the elicitation set-up. All authors have been involved in writing.

All authors contributed to aim and scope of Paper V. Landquist was the main developer of the consequence assessment approach and all authors were involved in writing.

Other work and publications not appended

- Larsson et al., (2011). *Environmental risks posed by shipwrecks.* In Swedish, *Miljörisker från Fartygsvrak*, pp. 48-53. The Swedish Maritime Administration.

- **Landquist, H.** (2013). *Method development for environmental risk assessment of shipwrecks.* Licentiate Thesis No R13:144, Chalmers University of Technology.

- **Landquist, H.** (2013). Environmental Risk Assessment of Shipwrecks: A Fault-tree Model for Assessing the Probability of Contaminant Release. *Integrated Environmental Assessment and Management (IEAM) by the Society of Environmental Toxicology and Chemistry (SETAC).*

- Hassellöv., I.M., Olsson, U., Ekberg, G., Östin, A., Simonsson, F., Larsson, C., Sender, U., **Landquist, H.,** Lindgren., J.F., Lindhe, A., Rosén, L. & Tengberg, A. (2014). *Environmental risks posed by shipwrecks.* In Swedish, *Miljörisker sjunkna vrak. Undersökningsmetoder och miljöaspekter.* Dnr: 1399-14-01942-6. Sjöfartsverket.

- Hassellöv., I.M., Olsson, U., Ekberg, G., Östin, A., Simonsson, F., Larsson, C., **Landquist, H.,** Lindgren., J.F., Lindhe, A., Rosén, L. & Tengberg, A. (2015). *Environmental risks posed by shipwrecks II.* In Swedish, *Miljörisker sjunkna vrak II. Undersökningsmetoder och miljöaspekter.* Dnr: 1399-14-01942-15. Sjöfartsverket.

- **Landquist, H.,** Lindhe, A., Rosén, L., & Lindgren, J.F. (2015). SWERA Deliverable 2.2. EU. BONUS.

- Lindgren, F.J, Hassellöv, I.M., **Landquist, H.** & Dahllöf, I. (2015). *Low concentrations of PAHs induce tolerance in nitrifying bacteria.* Frontiers in Marine Science, 2.

- Andersson, K., Brynolf, S., **Landquist, H**. & Svensson, E. (2016). *Methods and Tools for Environmental Assessment.* In: Andersson, K., Brynolf, S., Lindgren, F.J. & Wilewska-Bien (eds.). *Shipping and the Environment: Improving Environmental Performance in Marine Transportation.* Berlin, Heidelberg: Springer Berlin Heidelberg.

- Lindgren, J.F., Andersson, K., & **Landquist, H**. (2016). *Marine Spatial Planning and Shipwrecks.* In: Andersson, K., Brynolf, S., Lindgren, F.J. & Wilewska-Bien (eds.). *Shipping and the Environment: Improving Environmental Performance in Marine Transportation.* Berlin, Heidelberg: Springer Berlin Heidelberg.

- Etkin, D., French McCay, D., Horn, M., **Landquist, H.,** Hassellöv, I.M. & Wolford, A.J. (In prep). *Quantification of Oil Spill Risk*. In: FINGAS, M. (ed.) Oil Spill Science and Technology. Burlington, USA: Elsevier.

- **Landquist, H.,** Rosén, L., Lindhe, A. & Hassellöv, I.M. *Estimating consequences of discharge from potentially polluting shipwrecks.* (2015). Abstract, presentation. In proceedings of, Science, Policy, Society – bridging the gap between risk and science. SRA Europe, June 15-17.

- **Landquist, H.,** Rosén, L., Hassellöv, I-M., Lindgren, J.F., Norberg, T.& Lindhe, A. (2012). *Environmental risk assessment of shipwrecks: a fault-tree model for assessing the probability of contaminant release*. Poster, the SETAC North America 33rd Annual Meeting, Long Beach, November 11-15.

- Johansson, A.M., Hassellöv, I.M., Eriksson, L.B., Lindgren, F.J., Berg, A., Carvajal, G., **Landquist, H.** (2014). *Remote sensing for risk analysis of oil spills in the Arctic Ocean*. Poster at EGU, Wienna, Austria.

- Johansson, A.M., Hassellöv, I.M., Eriksson, L.B., Lindgren, F.J., Berg, A., Carvajal, G., **Landquist, H.** (2014). *Risk analysis of oil spill in the Arctic Ocean*. Poster at Arctic Frontiers, Tromsø, Norway.

- **Landquist, H.,** Rosén, L., Lindhe, A., Norberg, T., Hassellöv, I.M., Lindgren, J.F & Dahllöf, I. (2014). *A fault tree model to assess probability of contaminant discharge from shipwrecks.* Poster at Geo Arena – Mötesplats geologi, Uppsala, Sweden.

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Hanna Landquist
Gothenburg, 2016

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1. Introduction

The ability to identify adverse events that might possibly occur in the future, and to make good and relevant choices from among alternative actions that could be employed to manage such events, is a key factor in modern society. Understanding risk thus allows us to make rational decisions (Bernstein, 1996). Limited societal resources combined with numerous potential areas of need for these resources imply that prioritisation decisions are required. One of these resource-demanding areas is environmental protection and a specific area that has attracted growing attention is the problem of potentially polluting shipwrecks.

Polluting shipwrecks are a global and multi-faceted problem. Estimates indicate that several thousand wrecks litter the ocean floors (Michel et al., 2005). In Swedish waters alone, 2,700 wrecks (≥ 100 gross tonnage) warrant further investigation and more than 300 of these were assumed to pose an environmental threat as they may contain 1,000-15,000 tonnes of bunker oil (Larsson et al., 2011). Many shipwrecks have been deteriorating on the seabed for several years and many originate from the Second World War containing unknown amounts of oil and other hazardous substances. Oil can be present both as bunker and cargo, making it the most common hazardous substance in wrecks. Assessing risks posed by shipwrecks requires the adoption of a holistic perspective. The entire chain of events, from wreck condition and cargo to environmental conditions at the wreck site and external factors, must be taken into account to obtain a relevant grasp of the problem. The threat from shipwrecks requires attention, and there is a need for guidance, decision-making support and methods to assess and handle efficiently the environmental risks and facilitate resource allocation for mitigation measures (Paper I; Michel et al., 2005).

The environmental risk posed by each wreck is unique with regard to the probability of leakage and its potential impact. Each vessel will respond differently to external forces and environmental conditions are specific to each wreck location (Etkin et al., 2009). The effects of an oil discharge from a shipwreck will depend on when the oil is released, where the release occurs, the spreading rate of the oil slick and the type of oil (Michel et al., 2005). Oil discharged into a marine environment is harmful to living organisms (e.g. Kingston, 2002; Lindgren, 2015). Oil spills can also cause economic damage to property and market goods such as tourism and fisheries as well as non-market goods such as recreation (Fejes et al., 2011). The wide variety of factors influencing a potential discharge implies that there are also a number of uncertainties associated with risk assessments of shipwrecks, and hence also with possible measures aimed at mitigating the risks posed by shipwrecks.

Etkin (2009) argues that a reactive approach to oil leakage from a shipwreck would lead to higher response and damage costs compared to a well-planned, proactive oil removal operation. Nevertheless, it is very costly to remediate shipwrecks. It is estimated that remediation of one wreck could cost USD 1-100 million (Michel et al., 2005) and it is therefore not economically feasible to remediate every sunken shipwreck. The 300 or more wrecks only in Sweden mentioned previously would cost hundreds of millions of dollars to remediate. To deal with the problem of potentially polluting shipwrecks, there is a vital need for decision support methods to facilitate prioritisation of wrecks and identification of how available resources can be used most efficiently.

Shipwreck risk assessment requires knowledge from many fields and collaboration between several bodies to make relevant decisions regarding potential mitigation measures. A key aspect of utilising available resources efficiently is to facilitate cooperation between these bodies. The responsible authorities, such as the Swedish Agency for Marine and Water Management, the Maritime Administration, the Coast Guard, shipwreck remediation companies and researchers in Sweden and abroad, are just some examples of potential collaborative organisations.

An important means of providing decision support is to apply risk assessment practices that are widely employed in several disciplines, including engineering, ecotoxicology, public health and economics (Burgman, 2005). Risk assessment is part of risk management and includes *Risk identification*, *Risk analysis* and *Risk evaluation*. Several approaches to risk assessment specific to shipwrecks can be found in the literature (Alcaro et al., 2007; Etkin et al., 2009; Idaas, 2005; Louzis et al., 2009; Michel et al., 2005; NOAA, 2009; NOAA, 2013; SPREP and SOPAC, 2002; Ventikos et al., 2013; Ventikos et al., 2016). However, studies presented in this thesis show that current methods fail to provide a holistic and/or fully probabilistic risk assessment of shipwrecks. Consequently, it could result in inefficient use of societal resources and inadequate risk mitigation of potentially polluting shipwrecks due to a lack of well-founded decision input.

1.1. Aim and objectives

The overall aim of this thesis was to:

> *Develop, apply and evaluate a model for comprehensive risk assessment of potentially polluting shipwrecks.*

To meet the overall aim, the following specific objectives were defined:

- Compare and analyse identified current risk assessment methods for potentially polluting shipwrecks with regard to how these methods comply with an international standard for risk management.
- Suggest a generic framework for risk management and assessment of shipwrecks, including risk identification, risk analysis and risk evaluation.
- Develop a method to quantitatively estimate the probability of discharge of hazardous substances from shipwrecks.
- Develop an approach for consequence assessment of the discharge of hazardous substances from shipwrecks by combining existing methods for oil spill modelling and receptor sensitivity.
- Present a comprehensive model for conducting a risk assessment of shipwrecks, including a method for estimating the probability of discharge of hazardous substances and an approach for making a consequence assessment of such a discharge. The model should also provide a means for risk evaluation by comparison with acceptable risk levels or making an analysis of the relationship between risk mitigation and cost.

A structured framework for managing risks associated with shipwrecks provides necessary guidance on the important steps needed to handle this environmental problem. Understanding the risk arising from potentially polluting shipwrecks also entails handling uncertainties. To cope with uncertainty, a quantitative probabilistic approach is applied by using a logic tree model for estimating the probability of discharge of hazardous substances. An expert panel was also involved to gather information on uncertain aspects of the probability of discharge. Release of hazardous substances into the marine environment will give rise to environmental consequences and implications in socioeconomic terms. These effects must be addressed and a consequence assessment approach is therefore developed. A comprehensive model for making a risk assessment of potentially polluting shipwrecks is based on the probability estimation method and the approach to consequence assessment.

1.2. Scope of work

The appended papers are interlinked, as shown in Figure 1. Paper I presents a literature review of existing methods for risk assessment of shipwrecks and suggests a generic risk assessment framework for wrecks. The paper was published in 2013 and since then three new approaches have emerged and are discussed in Chapter 3. However, the main finding of the paper still holds: existing approaches lack key elements of a holistic risk assessment for shipwrecks.

Papers II and IV describe a fault tree method for probabilistic estimation of the discharge of hazardous substances from wrecks. This quantitative method facilitates an explicit uncertainty analysis. A generic estimation of the probability of an opening in the wreck is updated by site-specific and wreck-specific indicators, e.g. time since sinking, salinity, and water temperature. A total probability of discharge is estimated by combining the probability of opening with the rate of hazardous activities and the probability that hazardous substances are still contained in the wreck. The fault tree method provides the foundation for the VRAKA tool, an Excel-based tool for estimating the probability of discharge from shipwrecks. Paper III presents the structure and outcomes of a comprehensive expert elicitation process that provided further input to the fault tree method. Paper IV makes use of these results and novel methodology for incorporating site-specific and wreck-specific indicators in the risk model is presented.

In Paper V, a comprehensive model for making a risk assessment of potentially polluting shipwrecks is presented. The model is called VRAKA (the Swedish word for wrecking) and comprises the VRAKA method for probability estimation of discharge and a three-tiered approach for a consequence assessment of such a discharge.

VRAKA is developed and operationalised in the spread sheet program Microsoft Excel© with the add-in software Crystal Ball© for Monte Carlo simulations. The VRAKA Handbook is appended to the thesis (A1).

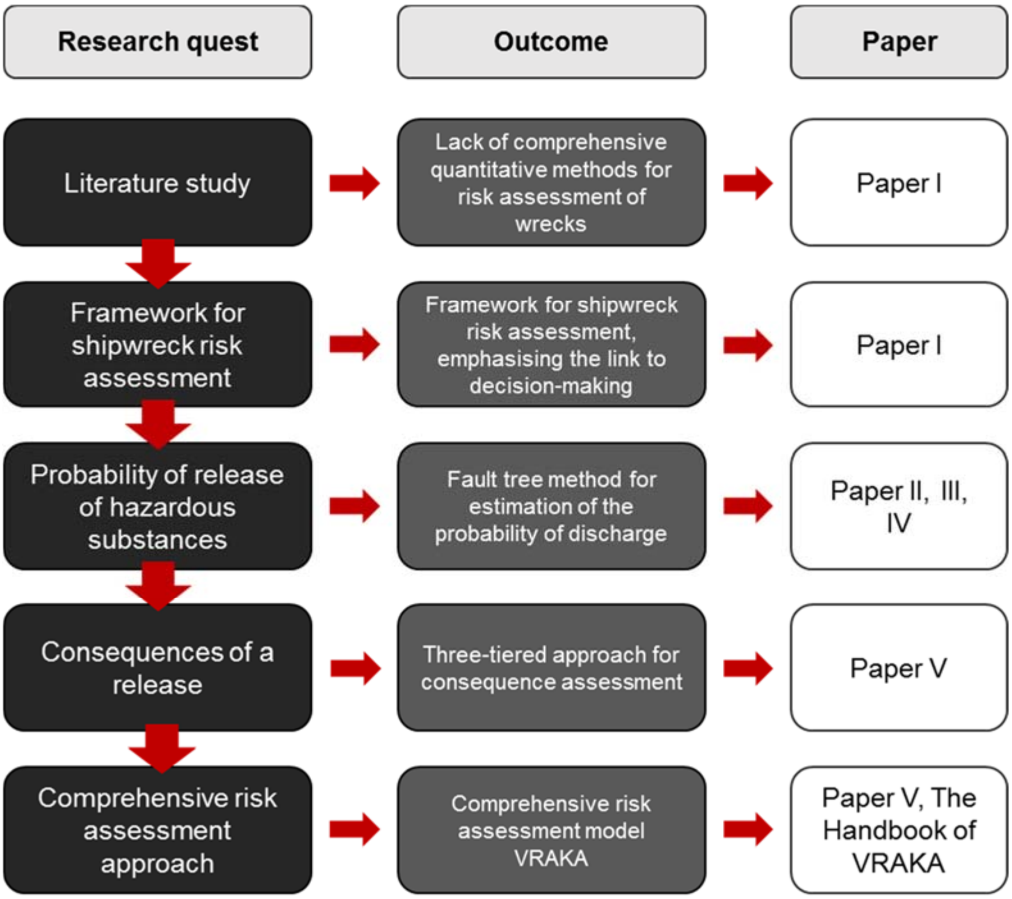

Figure 1. Schematic summary of the scope of the thesis in relation to the appended papers.

1.3. Limitations

The potential risk posed by shipwrecks is a complex problem involving risk assessment and management, decision-making and value-based judgement. It also involves a number of substances in wrecks on ocean floors all over the world. Encompassing the full complexity of shipwrecks is a vast endeavour and the following limitations of this work need to be highlighted:

- The suggested framework for risk management and assessment of shipwrecks describes the entire risk management process. However, the comparison between the identified methods focuses on risk assessment, as does the VRAKA method.

- The framework and model presented in this thesis are intended to facilitate a *proactive* approach and specifically the risk assessment of potentially polluting shipwrecks and the provision of decision support to deal with these risks. The assessment results aim to support prioritisation of wrecks and decisions regarding measures for preventing leakage of oil, although the actual process of selecting and performing preventive options or monitoring applied measures is not addressed in this thesis.

- There are shipwrecks all over the world containing a wide range of different hazardous substances. This thesis is focused on shipwrecks located in Scandinavian waters that contain oil. A wider geographical scope and expansion to other substances are possible future developments. The method for estimating the probability of discharge is not restricted to a specific area but it should be pointed out that the expert elicitation process that provides input is made using experts from Sweden and is based on the Swedish wreck population. The consequence assessment can for the less detailed tiers of the VRAKA method be performed in other parts of the world although the most elaborate tier is only applicable in Sweden. These methods provide a sound basis for further development for other locations.

2. Concepts of risk

The concepts of risk as we see them today originate from the Hindu-Arabic numbering system and deeper studies that took place during the Renaissance. In 1645, Blaise Pascal and Pierre de Fermat discovered the theory of probability, which is the core of the concept of risk, when solving a gambling problem (Bernstein, 1996). Etymologically, risk stems from the early Italian word *risicare*, meaning to dare. When viewing risk from that latter perspective there is a choice involved, as opposed to dependence on faith which was the prevailing view of life in the past (Bernstein, 1996).

Today many definitions exist (e.g. Aven et al., 2015) although a general view of risk is that it is the chance of an adverse event occurring within a specific time-frame and with specific consequences (Burgman, 2005). Another definition is that risk is a combination of the severity and probability of effects from a certain action, where severity is the nature and magnitude of the effects (Suter, 2007). A common definition that can, however, be deceptive to some extent is that of risk expressed as an expected consequence, i.e. the probability of an event multiplied by its consequence. With this definition an event with low probability and high consequence would not be separable from an event with high probability and low consequence (Kaplan and Garrick, 1981).

Aven (2010) argues that uncertainty should be included in the definition of risk and suggests that probability is only a tool to express or represent uncertainty and that risk is not limited to an initiating event, its consequences and the associated probabilities. Aven (2010) further discusses that probabilities assigned are based on background information and assumptions that could hide uncertainties and prevent them from receiving proper attention. Aven and Renn (2009) define risk as the "uncertainty about and severity of the consequences (or outcomes) of an activity with respect to something that humans value". ISO (2009) also includes uncertainty and defines risk as the "effect of uncertainty on objectives". Kaplan and Garrick (1981) prefer to state that a quantitative risk analysis should specifically answer the following three questions:

- What can happen?
- How likely is it?
- What are the consequences?

The risk approach chosen should be appropriate for the application at hand. In this thesis the approach by Kaplan and Garrick (1981) is applied, taking uncertainties into account when answering the last two questions above. This is described by IEC (1995) as "the combination of the frequency, or probability, of occurrence and the consequence of a specified hazardous event”. However, it should be noted that this thesis examines combinations of several hazardous events. Further discussion regarding the definitions of risk applied in this thesis is presented in Chapter 7.

There is an ambiguity surrounding risk, and the terminology differs greatly (Aven, 2012). Some of the commonly used definitions are shown in Table 1 and define the meaning of the different terms as used in this thesis. A number of examples for a shipwreck context are also given.

Table 1. Definitions of terms based on (Aven, 2012), ISO 31000 (2009) and IEC (1995) with some examples coupled to shipwreck risk assessment.

Aleatory uncertainty	The variation of quantities in a population. *E.g. Oxygen levels of the water around a shipwreck.*
Consequence	The outcome of an event affecting objectives. *E.g. Effects oil discharge in the marine environment.*
Epistemic uncertainty	A lack of knowledge about an unknown quantity. *E.g. Amount of oil contained in a shipwreck.*
Event	The occurrence of a particular set of circumstances. *E.g. Opening in a shipwreck though which oil can be discharged.*
Hazardous event	An event that can cause harm. *E.g. Construction work, Trawling or Shipping traffic possibly causing damage to a shipwreck.*
Hazardous substance	A substance with the potential to cause harm. *E.g. Bunker oil.*
Likelihood	The chance of something happening.
Risk	A combination of the frequency, or probability, of occurrence and the consequence of a specified hazardous event.
Risk analysis	A process employed to comprehend the nature of risk and to determine the level of risk.
Risk assessment	The overall process of risk identification, risk analysis and risk evaluation.
Risk criteria	The terms of reference against which the significance of the risk is assessed.
Risk evaluation	The process of comparing the results of risk analysis with risk criteria to determine whether the risk and/or its magnitude is acceptable or tolerable.
Risk identification	The process of finding, recognising and describing risks.
Risk management	The coordination of activities to direct and control an organisation with regard to risk. Includes risk assessment and risk reduction and control.
Risk management framework	A set of components that provide the foundations and organisational arrangements for designing, implementing, monitoring, reviewing and continually improving risk management throughout the organisation.
Stakeholder	A person or organisation that can be affected by, or perceive themselves to be affected by, a decision or activity. *E.g. the Swedish Maritime Administration, the Swedish Agency for Marine and Water Management, the Swedish Coast Guard, the Swedish Meteorological and Hydrological Institute. The Swedish Geological Survey, Maritime National Museums and the Swedish Defence Research Agency.*

2.1. Risk and shipwrecks

The large number of wrecks, the associated potential remediation costs, and the many factors affecting the consequences of a discharge from wrecks justify a risk assessment approach (Michel et al., 2005; Etkin et al., 2009). There are also major uncertainties associated with assessing the risk of hazardous discharges from wrecks, mainly because there are few measurements of how different activities, such as construction work or trawling, affect wrecks (Michel et al., 2005). The lack of measurements and available data implies that assessments including expert judgements are necessary and that their estimations are also uncertain. Moreover, site-specific conditions make generalisations concerning the effects of hazardous discharge difficult. This means that the handling of uncertainties is crucial in order to obtain useful results from a risk assessment of wrecks.

2.1.1. Hazardous activities

As mentioned in the introductory chapter, there are a number of factors that cause shipwrecks to deteriorate and ultimately this can lead to a discharge of hazardous substances such as oil. An obvious prerequisite is that the wreck still contains hazardous cargo or bunker fuel for propulsion. A number of hazardous activities that carry the possibility of inducing discharge of oil from wrecks have been identified through literature reviews (Louzis et al., 2009; Michel et al., 2005; Etkin et al., 2009) and brainstorming events with groups of experts in which Swedish waters are used as the focal area. Some activities are induced by humans whilst other activities have natural or environmental causes. Below is a description of each of the eight identified hazardous activities presented to experts when eliciting information for VRAKA. The elicitation procedure is presented in Paper III.

Construction work

Construction work can vary in extent and can include preliminary investigations and work ranging from aqua culture to pipelines, dredging, port construction and multi-use platforms.

Deterioration

Deterioration includes the wreck's general condition and how it is affected by corrosion and other types of degradation since the time the vessel sank.

Diving

Diving is described as one or more divers approaching a wreck they know of by boat. Divers anchor and dive around or inside the wreck. Material from the wreck can be brought to the surface.

Military activity
This includes activities such as basic seamanship exercises as towing, to mine sweeping and use of military force.

Shipping traffic
Shipping traffic involves everything from pleasure boats, ferry traffic, coast guard vessels and ice breakers to cruise ships, bulk carriers and container ships.

Storms/Extreme weather
This is defined as winds of at least 98-102 km/h (Storm).

Trawling
Trawling means fishing with everything from small trawls made of steel-reinforced wood close to the coast and in more shallow waters, to fishing with large steel trawls further out from the coast at considerable depth.

Unstable seabed
A varying amount of material on the seabed is moved over a distance that can also vary.

2.1.2. Site-specific and wreck-specific indicators

The probability and extent of the damage the specific hazardous activities can lead to are assumed to be dependent on a number of site-specific and wreck-specific indicators. These indicators were arrived at during brainstorming sessions with experts and through literature reviews (Louzis et al., 2009; Michel et al., 2005; Etkin et al., 2009; Sender, 2011). The indicators are (Paper III, IV):

- Average bottom water oxygen concentration
- Average bottom water salinity
- Average bottom water temperature
- Average bottom water current speed
- Average hull thickness
- Seabed character
- Ship use
- Time since sinking
- Water depth
- Wreck position on seabed

2.2. The risk management process

There are several frameworks that describe the risk management process (e.g. IEC, 1995; ISO, 2009). They are typically generic in the sense that they are not limited to one specific field of application and they share certain basic steps (Figure 2): *risk assessment*, consisting of *risk analysis* and *risk evaluation*, and *risk reduction and control* collectively complete a full risk management process.

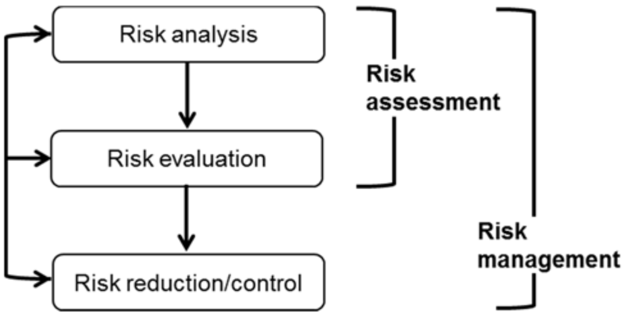

Figure 2. A simplified representation of the risk management process, based on IEC (1995).

An expanded framework is provided by ISO (2009) (Figure 3) where a broader presentation of the risk management process is given. In *establishment of the context*, the organisation sets the scope and risk criteria for the process. Within *risk identification*, the aim is to produce a comprehensive list of what might affect achieving the objectives*. Risk analysis* is the process of understanding the nature and determining the level of risk and should provide input for the risk evaluation step, which could act as support when making decisions related to the handling of risks. *Risk evaluation* involves comparing the results of the risk analysis with risk criteria and evaluating possible actions. This shows whether the risks found are acceptable or not. During the final step, *risk treatment*, one or more actions are chosen and implemented to mitigate the risk.

In order to enter into a dialogue with stakeholders and to ensure an exchange of information with relevant parties, communication and consultation are important during all the risk management phases. Monitoring and review should also be part of a risk management process, including providing input to improve the process, detecting changes that should be reflected in earlier stages, and identifying emerging risks (ISO, 2009).

Risk management can be a help to decision-makers when making informed actions and when prioritising between options (ISO, 2009). More specifically, it is through risk assessments and analyses information to support good decisions can be elicited (Aven, 2012).

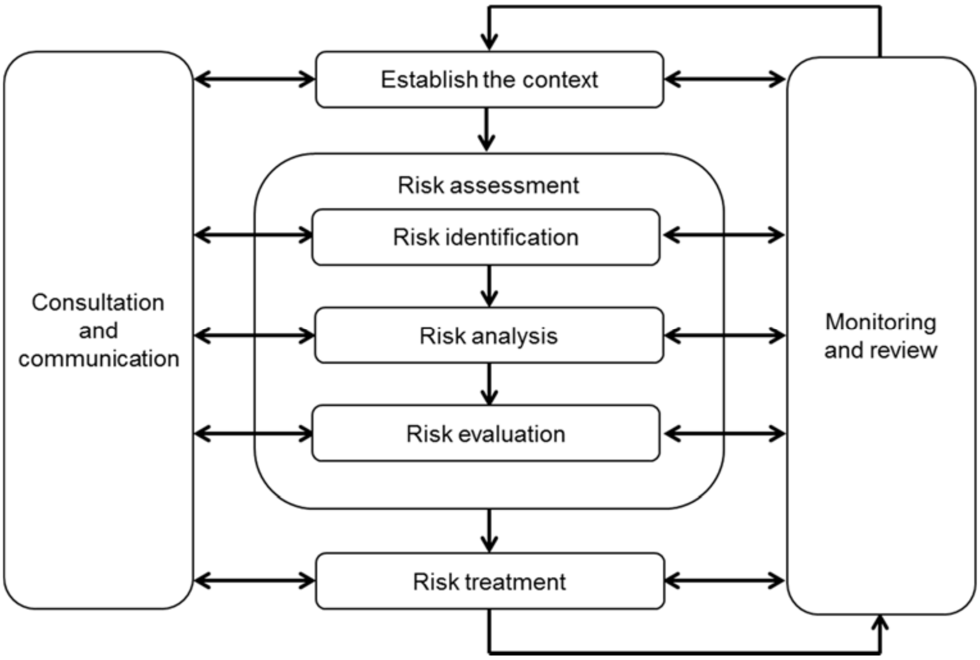

Figure 3. The risk management process after ISO (2009).

2.3. Risk assessment

As noted above, the purpose of risk assessment is to provide input and support to a decision-making process (Burgman, 2005). It is performed within many disciplines including medicine, engineering and environmental regulation (Suter, 2007). The main steps in risk assessment are *risk identification, risk analysis* and *risk evaluation* as described above (ISO, 2009).

Numerous tools are available for hazard and consequence identification, such as checklists and brainstorming, hazard matrices, hazard and operability analysis (HAZOP), failure modes and effects analysis (FMEA) and hierarchical holographic modelling (HHM). Several tools could be applied for the same hazard identification process in order to increase the potential to detect as many hazards as possible (Burgman, 2005), which is also the purpose of this step (ISO, 2009).

Risk analysis is performed to develop an understanding of the risk. The consequences and their likelihoods are determined. The analysis can be qualitative, semi-qualitative or quantitative and should include a sensitivity analysis. The type of analysis depends on the level of detail sought and other circumstances, such as the purpose of the risk assessment (ISO, 2009).

In the risk evaluation, identified levels of risk can be compared to pre-set criteria for risk acceptance in order to analyse whether the risk is acceptable. One means of evaluating risk against set criteria in practical terms is the use of the ALARP principle, i.e. "*as low as reasonably practicable*", where it is acknowledged that even if in most circumstances risk can be mitigated, the efforts involved to mitigate the risk to that extent are increasingly costly. (Jones-Lee and Aven, 2011; Burgman, 2005) (Figure 4).

There is a number of decision criteria available for stating the accepted risk. Preventing adverse effects, mitigating risk, and balancing costs and benefits, are some examples (Suter, 2007). Criteria of this nature can be termed utility-based and rights-based criteria where the former are based on a valuation of outcomes while the latter are focused on process and permitted action. An example of a utility-based criterion is *benefit-cost (probabilistic or deterministic)* which is aiming at identifying the alternative that produces the highest net benefit. Rights-based criteria are instead expressed as e.g. zero risk, where risk is eliminated independently of benefits and costs. Another example of a rights-based criterion is bounded or constrained risk, where the level of risk is constrained to a specific level or meets a specific criterion. Combinations of these types of criteria are also possible (Morgan and Henrion, 1990).

A range of methods are available to support the decision-making process and to evaluate if the set criteria have been met. Risk ranking is a simple form of risk comparison where risks are ordered. Risk classification involves assigning risks as e.g. acceptable or unacceptable (Suter, 2007), see also ALARP above. Examples of more elaborate techniques are Multi Criteria Decision Analysis (MCDA) and Cost-Benefit Analysis (CBA), where MCDA is a means of guiding the decision-maker by defining the all relevant criteria for evaluating the risk (Burgman, 2005). Cost-Benefit Analysis is an example of a method with an economic focus, measuring whether the benefits are greater than the costs for a particular action from a societal point of view (Hanley and Barbier, 2009). Furthermore, Cost-Effectiveness Analysis (CEA) is a means of finding the outcome with the least cost in relation to other outcomes rather than in absolute numbers (Munier, 2004).

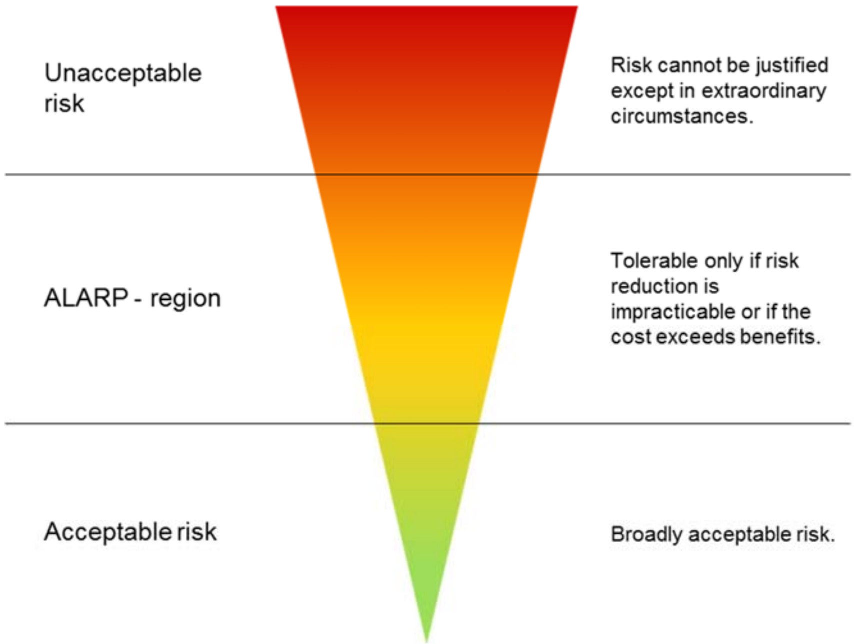

Figure 4. The ALARP-principle based on Burgman (2005).

2.4. Decision-making

A basic structure for the decision-making process is shown in Figure 5 (Aven, 2012). The structure is founded on the assumption that decision-making is a process where risk and decision analyses, e.g. CBA or MCDA, provide input. Informal managerial judgement and review should follow, to result in a decision. The risk management process and the decision-making structure do not conflict; rather, the former is an important component of the latter.

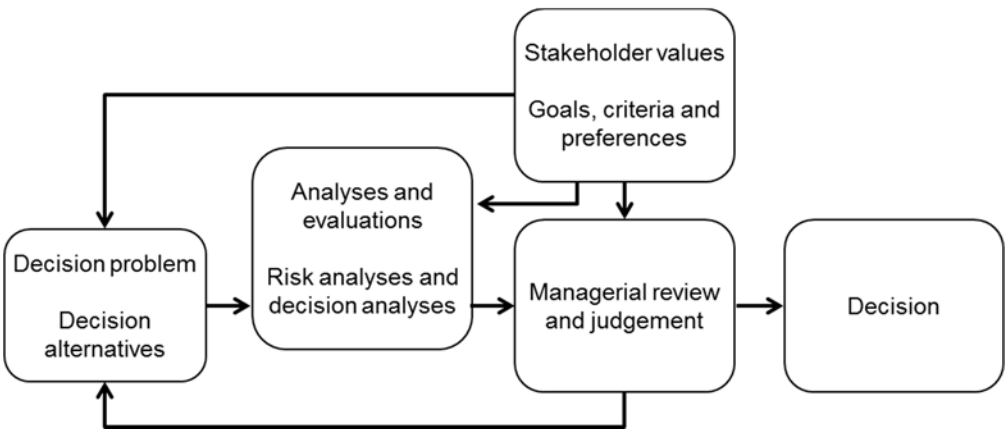

Figure 5. Basic structure of the decision-making process (Aven, 2012).

2.5. Uncertainty and probability

Two common denominators for problems concerning risk are that a decision needs to be made and that uncertainties are involved (Suter, 2007). Uncertainty is a far-reaching concept and can emerge from statistical variation, linguistic indistinctness, variability, inherent randomness, and so on (Morgan and Henrion, 1990). Potential sources of uncertainty are many, although uncertainty is in general categorised as one of two types: epistemic and aleatory. Epistemic uncertainty is assumed to be derived from a lack of data and aleatory (stochastic) uncertainty refers to intrinsic randomness and describes natural variability in populations (Kiureghian and Ditlevsen, 2009; Aven, 2012). However, purely aleatory uncertainties seem rare since they often have an epistemic component (O'Hagan and Oakley, 2004). Uncertainty can be defined as "*Imperfect or incomplete information/knowledge about a hypothesis, a quantity, or the occurrence of an event*" (Aven et al., 2015).

The quality of the risk assessment will largely depend on how uncertainties are dealt with. Uncertainties must be treated in a comprehensive, repeatable and transparent manner (Burgman, 2005). The aleatory type of uncertainty is determined by the circumstances and cannot be reduced, only acknowledged. However, the epistemic uncertainties can be reduced through increased information. There are several techniques for evaluating and handling uncertainties in risk analysis. One approach, applied in this thesis, is probabilistic risk analysis, also known as quantitative risk analysis, which can be used to estimate or cope with uncertainties regarding our knowledge about probability and associated consequences (e.g. Bedford and Cooke, 2001).

An important means of evaluating and handling uncertainty is to apply a Bayesian approach, facilitating a formal handling of subjective information. Around one hundred years after the theory of probability was formulated by Fermat and Pascal, as mentioned in the beginning of the chapter, Thomas Bayes discovered how new information could be mathematically combined with old information to provide better decisions (Bernstein, 1996). Bayesian probability is a belief-type approach an assessor can apply to rationally change a belief when new evidence is found (Hacking, 2001). When applying Bayes' theory, a prior distribution can be updated to a posterior distribution. The prior distribution is based on knowledge, including measurement data, and expertise, while the posterior distribution also acknowledges additional information, e.g. from a newly performed sampling campaign. The extensive use of the Bayesian approach can be attributed to the possibility of combining expert judgements with scientific evidence (Bedford and Cooke, 2001).

Furthermore, it is crucial to accept the fact that there is uncertainty in unknown unknowns, i.e. aspects that were not possible to know beforehand. It is simply impossible to include all relationships and variables (Metz et al., 2007).

Probability can be interpreted and expressed in different ways as either frequentist or subjectivist. A frequentist approach "defines the probability of an event´s occurring in a particular trial as the frequency with which it occurs in a long sequence of similar trials" (Morgan and Henrion, 1990, 48). The subjectivist, or Bayesian, definition views the probability of an event rather as "the degree of belief that a person has that it will occur, given all the relevant information currently known to that person" (Morgan and Henrion, 1990, 49). Although subjective, a Bayesian probability must, to be legitimate, follow the axioms of probability. For example, if a probability of an event occurring is p_i, the complement, i.e. the event not occurring, is $1-p_i$ (Morgan and Henrion, 1990). In this thesis, the Bayesian or subjectivist approach is applied since there is a lack of background information and observational data that could serve as input for the model. Moreover, every shipwreck is unique and an event in the form of a more extensive discharge is not repeatable.

A main focus of this thesis was to develop a method for calculating the probability of discharge of oil from shipwrecks. A Bayesian approach was applied to estimate probabilities as degrees of belief. An assessment of site-specific and wreck-specific parameters was applied to update earlier estimations of the probability of opening in a wreck. Since the background information and knowledge for the probability estimation is incomplete, the probability estimation itself is uncertain. Statistical distributions were thus assigned to represent the uncertainty of the probability estimations. The approach taken here is in accordance with the approach to probabilistic risk analysis described by, for example, Bedford and Cooke (2001).

3. Risk assessment approaches for shipwrecks

In Paper I, Evaluating the needs of risk assessment methods of potentially polluting shipwrecks, six methods and approaches for risk assessment of shipwrecks were analysed in order to evaluate if they could provide relevant decision support in this area. The identified methods were compared to, in the case for shipwrecks, relevant parts of the ISO standard for risk assessment, ISO 31000, Risk management – Principles and guidelines (ISO, 2009), see Section 2.1 for further details of the standard. More explicitly, parts assumed to be relevant correspond to the necessary steps for a comprehensive environmental risk assessment of shipwrecks and are presented in Table 2. Since publication, three further works present approaches for risk assessment of shipwrecks, NOAA (2013), Ventikos et al. (2013) and Ventikos et al. (2016). Some of the authors of the first publication authored the publication of the WORP project (NOAA, 2009) presented below as approach A. The latter publications share authors with the publication by Louzis et al. (2009), presented below as method F, but there is no clear reference between the earlier and latter works. These more recent methods are added to the original comparison and a summary is presented in Table 2. The full comparison is appended to Paper I as supplementary information.

3.1. Identified methods and approaches for environmental risk assessment of shipwrecks

The methods and approaches for risk assessment of wrecks were found in scientific papers and other official reports. Other material, such as the Nairobi International Convention on the Removal of Wrecks (International Maritime Organization, 2007), was not included since it was not intended as a framework for risk assessment of shipwrecks. Furthermore, the IMO Guidelines for Formal Safety Assessment (FSA) (International Maritime Organisation, 2002) is excluded since it is not a wreck-specific guideline.

The evaluated methods and approaches were:

A. The Wreck Oil Removal Program (WORP), aimed to use a scientifically-based approach to remove oil and focused specifically on trying to minimise costs and the risk of pollution from sunken commercial vessels (NOAA, 2009).

B. Michel et al. (2005) presented an oil release risk assessment guide for shipwrecks. The goal was stated as being to objectively analyse shipwrecks according to their potential threat of petroleum discharge and to provide guidance on addressing this issue.

Etkin et al. (2009) presented a similar guide, although taking into account both the probability of leakage and the impact of such a leakage occurring, in order to assess the environmental risk of shipwrecks. It was a strategic modelling approach to prioritise shipwrecks and the aim was to provide decision support for authorities.

C. DEvelopment of European Guidelines for Potentially Polluting Shipwrecks (DEEPP) aimed to provide European coastal states and national administrations with guidelines and criteria to handle the environmental threat of shipwrecks (Alcaro et al., 2007).

D. The Norwegian Pollution Control Agency (NPCA) described a wreck project in three phases: registration, priority ranking and required action. The aim was to have a complete overview of shipwrecks along the Norwegian coast (Idaas, 2005).

E. The Pacific Ocean Pollution Programme (PACPOL) within the South Pacific Regional Environment Programme (SPREP) was aimed at pollution of the marine environment from ship-based sources. This specific strategy was aimed at e.g. preventing or mitigating the negative impact of shipwrecks (SPREP and SOPAC, 2002).

F. A risk analysis strategy for shipwrecks in Greek waters was presented by Louzis et al. (2009). It was aimed at oil leakage and was based on the IMO Formal Safety Assessment (2002).

G. NOAA (2013) presented a comprehensive method for risk assessment of potentially polluting wrecks in U.S. waters. Pollution potential was estimated as well as the consequences of a range of spills. Possible response alternatives were also explored.

H. Ventikos et al. (2013) presented the development of an application for risk analysis of shipwrecks in Greek waters. A database was developed, an approach for risk assessment was presented and finally GIS tools were used in the visualisation of data and results.

I. In "Enhanced decision making through probabilistic risk assessment: Focusing on the situation in Greece", Ventikos et al. (2016) presented a method for estimating the probability of release using dynamic fault tree modelling. Consequences were estimated qualitatively and then combined with the probability using a risk matrix.

3.2. Comparison with an international standard for risk management

Each of the methods found were graded on a four-point scale with respect to each of the selected parameters from the ISO standard. The parameters were evaluated from "not considered at all", "considered", "fulfilled to some extent", to "fulfilled to a large extent". A summary is presented in Table 2.

Table 2. The results of the comparison of risk assessment methods for shipwrecks. A = The Wreck Oil Removal Programme (NOAA, 2009), B = Potentially polluting wrecks in marine waters (Michel et al., 2005), C = The DEEPP project, Development of European guidelines for Potentially Polluting shipwrecks (Alcaro et al., 2007), D = The Norwegian Pollution Control Authority (Idaas, 2005), E = The South Pacific Regional Environment Programme (SPREP and SOPAC, 2002), F = Louzis et al. (2009), G = The method by NOAA (2013), *H = The approach by* Ventikos et al. (2013) *and I = Ventikos et al. (2016).*

		Method								
		A	B	C	D	E	F	G	H	I
	Establishment of the context									
	• Scope	Fulfilled to a large extent	Fulfilled to a large extent	Fulfilled to a large extent	Considered	Fulfilled to a large extent	Fulfilled to a large extent	Fulfilled to a large extent	Fulfilled to a large extent	Fulfilled to a large extent
	• Defining risk criteria		Considered	Considered	Considered	Considered	Considered	Fulfilled to some extent	Considered	Considered
	- *Ship selection*	Fulfilled to some extent	Fulfilled to some extent	Fulfilled to some extent	Considered	Fulfilled to some extent	Considered	Fulfilled to a large extent	Fulfilled to some extent	Fulfilled to some extent
	- *Geographic coverage*	Fulfilled to a large extent	Fulfilled to a large extent	Fulfilled to some extent	Considered	Considered	Considered	Fulfilled to a large extent	Considered	Considered
Risk assessment	**Risk identification**									
	• Sources of risks	Fulfilled to a large extent	Fulfilled to a large extent	Fulfilled to a large extent	Fulfilled to a large extent	Fulfilled to some extent	Fulfilled to some extent	Fulfilled to some extent	Fulfilled to some extent	Fulfilled to some extent
	• Areas of impact	Fulfilled to some extent	Fulfilled to a large extent	Fulfilled to some extent	Considered	Fulfilled to a large extent	Fulfilled to some extent	Fulfilled to a large extent	Fulfilled to some extent	Fulfilled to some extent
	• Events	Fulfilled to a large extent	Fulfilled to a large extent	Fulfilled to a large extent	Fulfilled to some extent	Fulfilled to some extent	Considered	Fulfilled to some extent	Fulfilled to some extent	Fulfilled to some extent
	• Causes of events	Fulfilled to a large extent	Fulfilled to a large extent	Fulfilled to some extent	Considered	Fulfilled to some extent	Fulfilled to some extent	Fulfilled to a large extent	Fulfilled to some extent	Fulfilled to some extent
	Risk analysis									
	• Estimation of consequences	Fulfilled to a large extent	Fulfilled to a large extent	Fulfilled to some extent	Considered	Fulfilled to a large extent	Considered	Fulfilled to a large extent	Fulfilled to some extent	Fulfilled to a large extent
	• Estimation of likelihood /probabilities of consequences	Fulfilled to a large extent	Fulfilled to a large extent	Considered	Fulfilled to some extent	Fulfilled to a large extent	Considered	Fulfilled to a large extent	Fulfilled to some extent	Fulfilled to some extent
	• Risk estimation									
	- *Qualitative*		Fulfilled to some extent	Fulfilled to a large extent	Considered	Considered	Fulfilled to some extent			
	- *Semi-quantitative*		Fulfilled to some extent					Fulfilled to a large extent	Considered	Considered
	- *Quantitative*							Fulfilled to some extent		
	• Uncertainty analysis		Fulfilled to some extent		Considered		Considered	Fulfilled to some extent	Fulfilled to some extent	Fulfilled to some extent
	• Sensitivity analysis									Fulfilled to some extent
	Risk evaluation									
	• Comparison of risk levels with risk criteria			Fulfilled to some extent	Fulfilled to some extent	Fulfilled to some extent	Fulfilled to some extent	Fulfilled to some extent	Fulfilled to some extent	Fulfilled to some extent
	• Consideration of risk-reduction alternatives	Considered	Considered	Fulfilled to some extent	Considered	Considered	Considered	Fulfilled to some extent		
	Legend; Level of fulfilment									
	Fulfilled to a large extent	Fulfilled to a large extent								
	Fulfilled to some extent	Fulfilled to some extent								
	Considered	Considered								
	Not considered									

The comparison in Paper I showed that there was no comprehensive method for risk assessment of shipwrecks. The main weaknesses found were that many of the methods were qualitative and in general did not include sensitivity or uncertainty analysis. Overall, risk evaluation did not correspond to the level "fulfilled to a large extent". The methods found provide some guidance but none provide comprehensive support for decision-making with regard to shipwrecks. To some extent, the new methods comprised uncertainty analysis and NOAA (2013) also incorporate a quantitative probabilistic method for consequence assessment, although not regarding the probability of discharge.

Ventikos et al. (2013) and Ventikos et al. (2016) provide partly qualitative estimations and Ventikos et al. (2013) includes uncertainty analysis while Ventikos et al. (2016) includes both sensitivity analysis and addresses the issue of uncertainty. It should also be pointed out that some of the approaches compared are at the preparatory stage while e.g. NOAA (2013) and Idaas (2005) are actually applied to a larger number of wrecks. In summary, NOAA (2013) and Ventikos et al. (2016) are the most developed approaches according to the comparison presented in Table 2 but there is still no fully probabilistic comprehensive risk assessment method for shipwrecks that provides decision support in relation to this threat. Lack of holistic risk assessment and decision support for shipwrecks could potentially lead to inefficient allocation of resources for risk mitigation. The comparison presented here and in Paper I forms the basis for the development of the framework and model for probabilistic risk assessment of shipwrecks presented in this thesis. The framework clearly states the parts that should be included and stresses the link between risk management and decision-making. The suggested framework is presented in more detail in in Chapter 4 and in Chapter 6 the developed model is described.

4. A risk management framework for potentially polluting shipwrecks

Environmental risk management of shipwrecks is complex and should therefore be performed in a structured way. A generic framework for risk management of shipwrecks was suggested in Paper I (Figure 6Figure 1), based on ISO (2009), which is an international standard. The purpose was to emphasise the link between decision-making and risk management and stress that risk assessment is an essential basis for decision-making. Certain additional parts were added to the original guidelines to stress, for example, the communication of results to stakeholders and the need to handle uncertainties.

Exchange of information and communication are important in this type of procedure since it is essential that those responsible for implementing the results are well informed about the basis for possible decisions. Risk management is an iterative process and stakeholders should be continuously involved in the different steps. A review should be made to incorporate new information and update parts of the risk management work during the process if necessary (ISO, 2009). Furthermore, the complexity implies that a team of experts should be involved to ensure that knowledge of marine activities, the physical properties of a ship, the risk assessment process and other factors are duly considered.

The framework presents a holistic risk management structure for shipwrecks and is based on well-established views of risk management. Only by applying a comprehensive framework and adopting a holistic view of the problem can a full risk management process and assessment be made. When a framework is in place, methods can be developed that are well suited to the purpose of each specific part and to the process as a whole.

The framework advocates proactive risk management to mitigate the risk of pollution from shipwrecks. However, risk assessment cannot be the sole source of information input behind a decision, aspects not included in the risk assessment should also be considered in the decision-making process (Aven, 2003).

In order to implement the framework in practice, it is necessary to use an adequate set of methods and tools. Largely generalised assessments are due to the complex cause-and-effect chains of risks involved with shipwrecks, not likely to provide useful results and tools should therefore be chosen with care. Furthermore, uncertainties are assumed to be considerable and should be handled properly by adopting a quantitative, probabilistic approach. Development of methods and tools for making a risk assessment of shipwrecks is initiated and presented in Chapter 6 and in Papers I-V in this thesis.

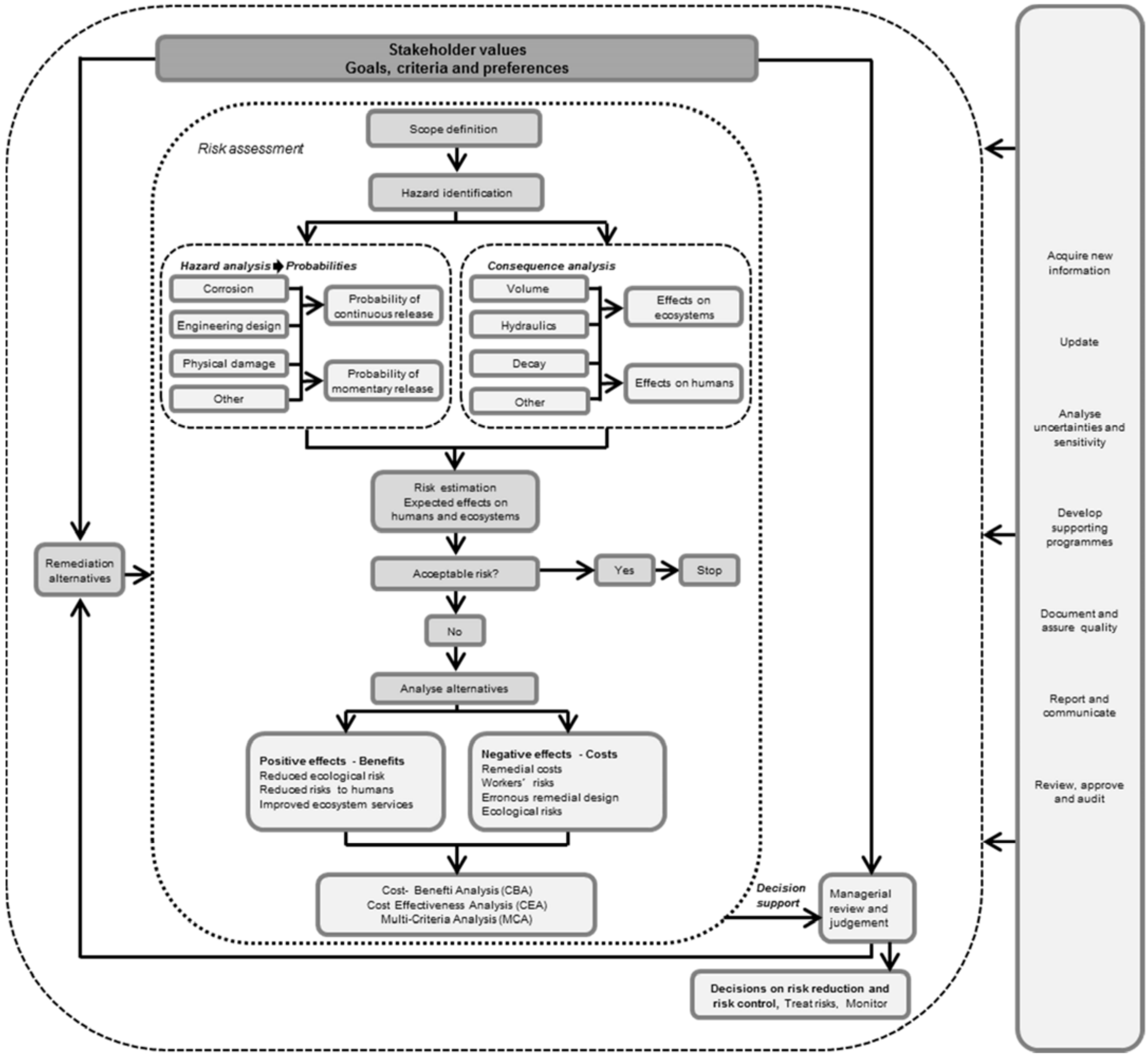

Figure 6. Generic framework for risk management and assessment of potentially polluting shipwrecks (Paper I).

5. Methods

This chapter describes the methods applied in the appended papers (Figure 7). The fault tree approach is used largely in Papers II and IV, and likewise Monte Carlo analysis, as means for estimating the probability of discharge of hazardous substances. Expert elicitation and the SHELF package (Sheffield Elicitation Framework) are applied in Paper III for obtaining input data for VRAKA. The Digital Environmental Atlas and the oil spill trajectory model Seatrack Web are used in Paper V. The theory for Paper I, risk assessment and management, is described in Chapter 2.

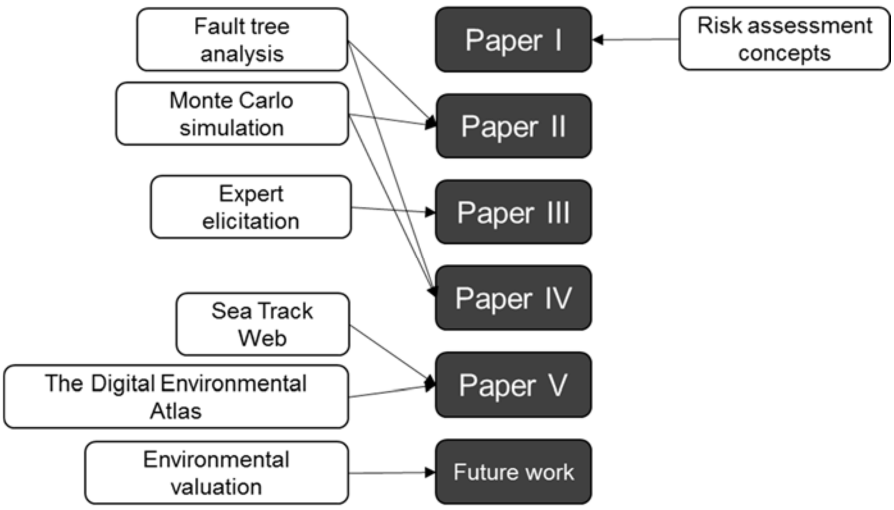

Figure 7. Overview of method application in Papers I-V.

5.1. Fault tree analysis

Logic trees, such as fault and event trees linking hazardous events and processes, have a wide range of applications (Burgman, 2005). An event tree describes subsequent events following a starting event and the final outcomes for different scenarios can be specified. Fault trees on the other hand seek to find the actions or events that cause such an initiating event. The fault tree emerges from basic events and passes via intermediate events to the analysed top event (Bedford and Cooke, 2001). An example of a fault tree is shown in Figure 8.

In a fault tree, several logic gates describe how the underlying events are connected (Bedford and Cooke, 2001; Burgman, 2005; Roberts et al., 1981). In this thesis, the AND and OR gates are applied. The AND gate defines an outcome where all the input events must occur simultaneously while the OR gate describes an outcome where only one of the input events must occur (Roberts et al., 1981). Mathematical descriptions of the two gates applied are provided in Equations 1 and 2, where *P* represents probability and index *i* represents an event in the fault tree.

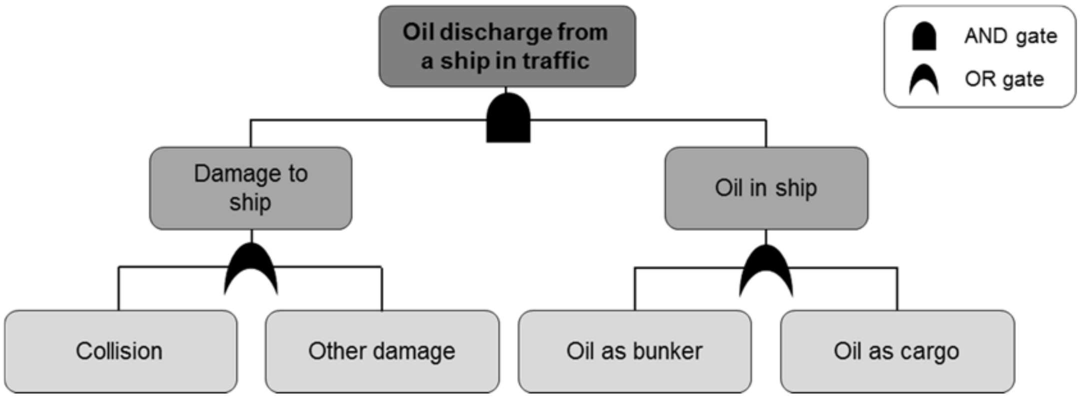

Figure 8. Example of a fault tree. Simplified description of a potential oil discharge from a ship in traffic.

$$P_{Occurence\_OR} = 1 - \prod_i (1 - P_i) \qquad \textit{Equation 1}$$

$$P_{Occurence\_AND} = \prod_i P_i \qquad \textit{Equation 2}$$

5.1. Monte Carlo simulation

Monte Carlo simulation is a technique applied in uncertainty analysis (e.g. Bedford and Cooke, 2001). It is based on random sampling and provides a means to cope with uncertainty in input information and results (Burgman, 2005). In VRAKA, input data is provided as ranges or probability distributions. Through Monte Carlo simulation, the outcome estimate sought is calculated using random sampling of the input distributions for a set number of iterations (see Figure 9 for a schematic visualisation). A probability distribution is obtained that represents the whole spectrum of possible outcomes rather than a point value. This technique facilitates sensitivity and uncertainty analysis (e.g. Bedford and Cooke, 2001; Burgman, 2005).

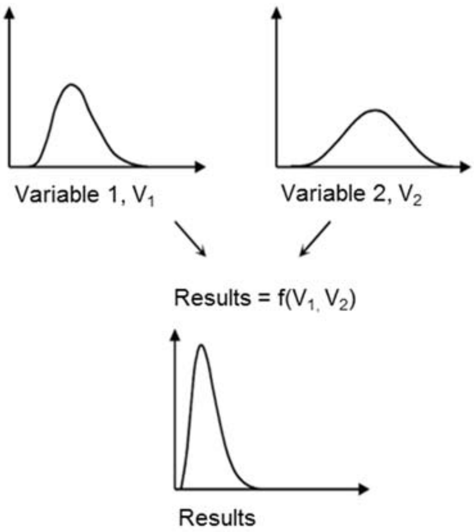

Figure 9. The concept of Monte Carlo simulation according to Lindhe (2010). Input information is given as distributions, and results are presented including uncertainties.

5.2. Expert elicitation

Shipwreck risk assessment is associated with uncertainties. Lack of measurable data or difficulty obtaining data due to cost or other conditions, such as the depth of the wreck, complicate the risk assessment. One means of gathering or estimating this type of information and reducing the uncertainties of the outcome is to ask for an expert opinion and subjective probabilities (Bedford and Cooke, 2001).

5.2.1. Experts, heuristics and biases

Expert judgement is almost unavoidable in environmental risk assessment. When empirical evidence or extrapolations are not available, experts can step in. They can estimate intervals and make point estimates or statistical distributions by using frequency concepts of probability without any measurement information (Burgman, 2005). An expert could, for example, be someone with the best available knowledge about the quantities of interest (Garthwaite et al., 2005), or a person with a great deal of training and knowledge in a specific field who provides an opinion (Ayyub, 2001).

People make judgements under uncertainty based on a number of heuristic principles. These are strategies or instinctive processes that reduce a complex question to simpler judgements. A couple of heuristics might be useful but can also lead to serious errors (Tversky and Kahneman, 1974). Heuristics mentioned by Tversky and Kahneman (1974) include: (1) *representativeness,* (2), *availability* and (3) *adjustment and anchoring*.

Tversky and Kahneman (1983) describe *representativeness* as estimated correspondence between a sample and a population or an outcome and a model. Alternatively, it could be the degree to which A is representative of B or resembles B (Tversky and Kahneman, 1974). Representativeness is specifically relevant when eliciting conditional probabilities where the expert might assess probability by how well outcome A represents model B rather than the probability of obtaining outcome B given model A (O'Hagan et al., 2006). The conjunction fallacy is one type of cognitive bias that can be attributed to representativeness. The probability of the conjunction, P(A&B) cannot be larger than the constituting probabilities P(A) and P(B), as the former is described using parts of these subsets (or the whole subsets if P(A) and P(B) are equal). However, the conjunction can be more representative than each of P(A) or P(B), which is why an error could be made. Another difficulty is to separate P(A|B) from P(B|A), known as the inverse fallacy (Villejoubert and Mandel, 2002).

Availability can be applied when assessing a frequency or probability. Frequent events are more easily recalled than less frequent events and the judgement is based on the ease the occurrence can be brought to mind (Tversky and Kahneman, 1974). The easier it is to recall an event, the higher the assessment of probability. An event with low frequency but high media coverage would thus also be assigned a high probability (O'Hagan et al., 2006). If, however, the assessor or expert has great personal experience of the problem that needs to be assessed, this heuristic might perform quite well (Morgan and Henrion, 1990).

Anchoring and adjustment refer to when people make judgements based on an initial value and then adjust that judgement to reach a final assessment (Tversky and Kahneman, 1974). However, there is a tendency towards not adjusting the final value sufficiently and the estimate is biased with regard to the initial value. The anchoring and adjustment effect can apply to any kind of quantitative judgement (O'Hagan et al., 2006).

Both experts and laymen provide assessments influenced by heuristics even if some elementary errors can be avoided if the expert is trained in the use of statistics. Heuristics can be a very effective means of making decisions although understanding the heuristics can lead to better decisions under uncertain conditions (Tversky and Kahneman, 1974). The process needs to be constructed in a way that the influence of heuristics and bias in the elicitation are minimised. Anchoring effects could, for example, be handled in part by carefully choosing the order of the questions posed to the expert. The process could encourage analytical thinking by, for example, applying aids and the experts' experience should be considered in relation to possible anchoring and availability effects (O'Hagan et al., 2006).

5.2.2. Stakeholders

Public concern and awareness of the many aspects of risk has become stronger due to the growth in communications, availability of information and scientific advances (Aven, 2012). A person or organisation that is particularly affected by the consequences of an environmental management decision is called a stakeholder (Suter, 2007). There are also definitions containing non-human entities, such as endangered animals and plants (Burgman, 2005). The public as a whole can have an interest in environmental decisions and decisions not accepted by those affected would be politically unacceptable. The general public and the stakeholders that are affected specifically by the decision should be separated and consequently the latter group is smaller. It could be necessary to involve a larger group from the general public in addition to the stakeholders in order to balance the input since the stakeholders tend to be biased (Suter, 2007).

When using stakeholders as a source of information and input for decision-making, it is important that their knowledge is used effectively. This involves, for example, choosing the right stakeholders for the problem at hand, eliciting information rigorously and applying appropriate analysis techniques. There should be a clear statement and communication of the purpose of the assessment to the stakeholders. A clear and honest communication process throughout the assessment is necessary for effective dialogue (Glicken, 2000).

An expert could be a stakeholder and vice versa. In this thesis work, numerous experts have been involved in the expert elicitation processes and a large number of stakeholders have been involved e.g. in reference groups. However, some of the stakeholders were also brought in as experts and vice versa.

5.2.3. Elicitation methods

Several approaches, general suggestions, methods and guidelines for eliciting expert opinion and subjective probabilities are described in the literature (Walls and Quigley, 2001; Cooke, 1991; Morgan and Henrion, 1990; Meyer and Booker, 2001; Jenkinson, 2005; Phillips, 1999; Cooke and Goossens, 2000; Kuhnert et al., 2010; Ayyub, 2001). However, consensus prevails regarding the broader concept and Jenkinson (2005) suggests the following process:

1. Background and preparation
2. Identifying and recruiting experts
3. Motivating the experts
4. Structuring and decomposition
5. Probability training
6. Elicitation

The first step involves identifying the variables to be assessed. Here the facilitator also has the opportunity to acquire knowledge of the specific field in order to communicate effectively with the experts. Preparation of the elicitation session and arranging the required documents are also part of the first step (O'Hagan et al., 2006).

The second step, identifying and recruiting experts for elicitation, is a very important stage. Certain criteria that could be applied when selecting experts are provided by Hora and Von Winterfeldt (1997): *tangible evidence of expertise, reputation, willingness to participate and availability, understanding of the general problem area, lack of an economic or personal stake in the potential findings and impartiality*. O'Hagan et al. (2006) also point out that it might be worth the effort to investigate the expert's level of statistical understanding. If this knowledge is poor, training could be provided at a later stage.

The third step involves motivating the experts. O'Hagan et al. (2006) suggest that experts should be informed about why their judgement is sought and how the results of the elicitation will be used. Furthermore, it is suggested that a record is kept and that its purpose is explained clearly to the experts. Jenkinson (2005) also points out that it is important to establish a good bond with the experts and provide them with support and encouragement in the elicitation process. This is followed by structuring and decomposition, which is a stage of defining precisely the quantities to be elicited and the format of the elicitation (Cooke and Goossens, 2000).

Expert knowledge can be divided into substantive and normative. The first applies to knowledge and experience of the field in question while the latter is related to the form of response desired in the elicitation. The response mode could be probabilities, ranks or pairwise comparisons (Meyer and Booker, 2001). Some experts might be familiar with the response mode chosen and some may not, thus highlighting the need for probability training.

The five initiating steps are taken in preparation for the actual elicitation. Garthwaite et al. (2005) describe the process of eliciting probability distributions as follows:

1. *The setup.* Incorporate the five initiating steps already described.
2. *Elicit* the summaries of the expert's distributions regarding the areas of interest. This is the main stage of the expert elicitation process.
3. *Fit a probability distribution* to the elicited summaries in step 2.
4. *Assess the adequacy of the elicitation*. Here the elicitation can also go back to step 2 to elicit more summaries in an iterative process.

5.2.4. SHELF

SHELF is an expert elicitation framework developed by O'Hagan and Oakley (2010). It is openly available to anyone who wishes to use it and it is applied in this thesis. It provides a formal procedure for an elicitation process and improves quality and defensibility. SHELF is a tool and provides advice and guidance on the process for a facilitator. SHELF can be applied to elicit distributions for one or more experts as a group and the package provides several possibilities for eliciting a distribution. These are: the P (Probability) method, where probabilities are derived from the experts; the Q (Quartile) method, where the expert is asked to estimate the median and upper and lower quartiles; the R (Roulette) method, where the facilitator asks for probabilities of ranges of values within ten bins, and the T (Tertile) method, where the median and upper and lower tertiles are requested from the expert.

Initially, the elicitation should be done individually, after which the group makes a common elicitation. Each of these steps is presented in forms the facilitator and experts can use to go through the elicitation process. During elicitation, the experts are shown distributions corresponding to their answers. These should be computed in real time and the SHELF package includes procedures adapted to the statistical software package R, Rpanel, for performing this. By visualising the distributions, the experts are given the opportunity to provide feedback and revise their estimations in order to produce the distribution they believe in.

5.3. Oil spill trajectory modelling and Seatrack Web

In order to adequately determine the spreading of oil discharge in the marine environment, oil spill trajectory modelling is required. One example of such a tool is the Spill Impact Model Application Package (SIMAP), which comprises three-dimensional models for biological effects and oil fates. It can be run in a stochastic mode for analysis of the probability of different outcomes (McCay et al., 2004).

Another tool that provides the possibility of modelling oil spill trajectories, and which is applied in the Baltic Sea, is Seatrack web. Due to its availability to Swedish authorities, it has been chosen for the work at hand. The user provides the date, location and amount of possible discharge and Seatrack Web uses available meteorological and hydrological data to estimate a trajectory. Results are provided as amounts of hazardous material transported to the seabed, water surface and shore (SMHI, 2015; SMHI, 2011). The trajectory estimation is based on forcing (forecasts of flow and wind fields) and the oil drift model PADM (Particle Dispersion Model), and is presented in a graphical, web-based interface. The forcing fields are based on ocean and weather forecasts at SMHI (Swedish Meteorological and Hydrological Institute), i.e. the HIRLAM (High Resolution Local Area Modelling) for weather forecasts, and HIROM (High Resolution Operational Model for the Baltic) for ocean forecasts. Longer periods of forcing weather fields are modelled by the European Centre for Medium-Range Weather Forecasts. The principal areas covered by Seatrack Web are the Baltic Sea, Kattegat, Skagerrak and the North Sea to around 3° east. The PADM has been developed by the Danish Maritime Safety Administration (DAMSA) and SMHI and the graphical interface by SMHI. For further technical details, see Liungman and Mattson (2011).

5.4. Oil spill impact and the Digital Environmental Atlas

Estimation of oil spill impact should contain ecological and socioeconomic aspects. Tools that can aid the analysis of the impact could include e.g. sensitivity mapping of the coastline, mapping of tourist areas, the businesses possibly affected, environmentally protected areas, sensitivity estimations of species in the area.

The Digital Environmental Atlas is applied in this thesis and maps the Swedish coast according to sensitivity to oil spill and physical characteristics. The sensitivity mapping is based on the type of shore, its exposure and to some extent on biological prerequisites. (Kulander et al., 2010). The tool is openly available on the web and is administered by the County Administrative Board of Västra Götaland (County Administrative Board of Västra Götaland, 2015).

6. VRAKA – a comprehensive model for risk assessment of shipwrecks

VRAKA – the comprehensive model for risk assessment of shipwrecks, was developed based on the conclusions from Paper I and the framework for risk management of shipwrecks. The purpose of VRAKA is to facilitate risk assessment, including *risk analysis* and *risk evaluation* (Figure 10). Risk analysis involves *scope definition*, *hazard identification* and *risk estimation*. Scope definition is a task for the assessor, i.e. it involves deciding which wrecks will be included in the assessment while hazard identification and risk estimation are performed in VRAKA. VRAKA also provides a means for risk evaluation. As shown in
Figure 10, VRAKA can be applied to provide decision-support regarding prioritisation of mitigation measures for wrecks. Aspects linked to implementation and monitoring as part of risk reduction and control are not included.

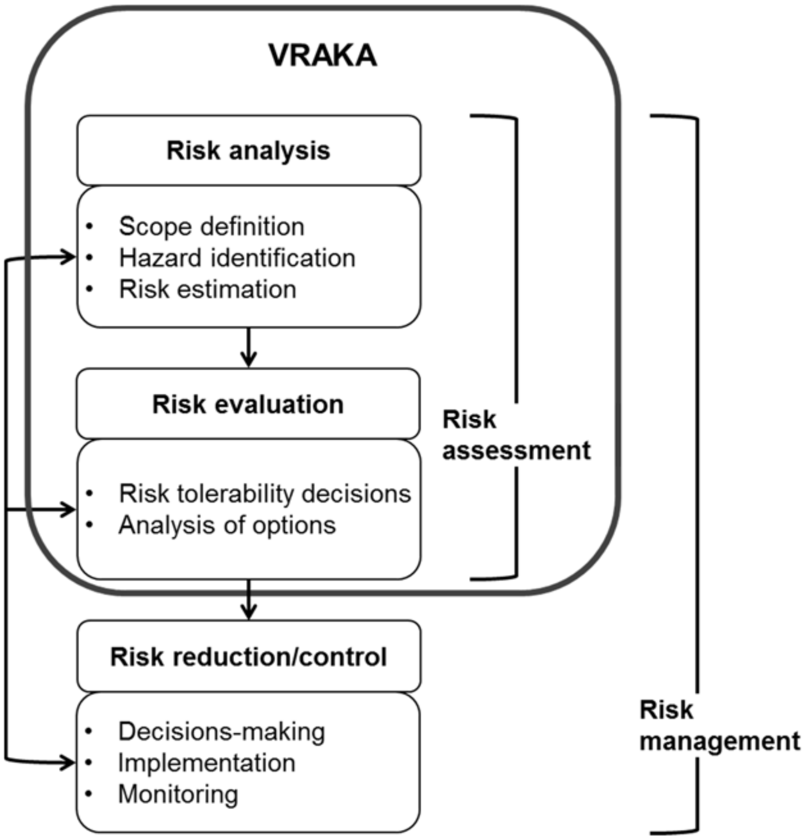

Figure 10. VRAKA in relation to the risk management process after (Paper IV).

The VRAKA model can be described as consisting of three parts: Part I – Estimation of the probability of discharge, Part II – Consequence assessment and Part II – Risk evaluation (Figure 11). Part I is a method based on fault tree analysis describing the combination of activities possibly leading to an opening in the wreck and a possible discharge of hazardous substances. Part II is an aggregation of methods for consequence assessment of a potential discharge. The assessment can be performed according to a three-tiered structure. The choice of tier, or level of detail, is made with respect to level of ambition and available resources. Part I is described in Papers II-IV and is summarised in this chapter in Section 6.1. Part II is described in Paper V and is also summarised in this chapter in Section 6.2. Part III, risk evaluation, is discussed further in Section 6.3.

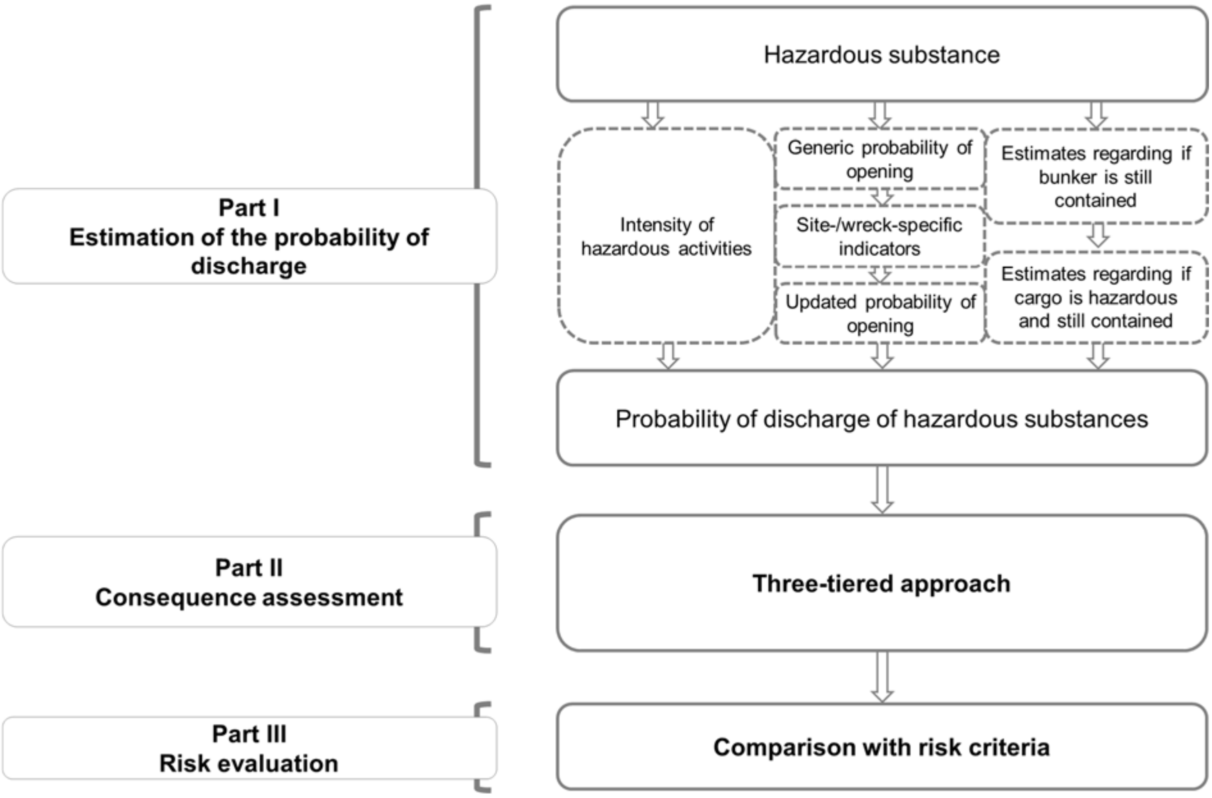

Figure 11. The three parts of VRAKA.

6.1. Part 1 – Estimation of the probability of discharge

The probability of discharge is modelled using a fault tree (Figure 12) and two events are deemed necessary for discharge; an opening in the wreck occurs and hazardous substances are present. An opening in the wreck is assumed to be a result of one or more activities, and hazardous substances are assumed to be present if either the fuel or bunker is hazardous and is still contained in the wreck. The development of the VRAKA fault tree model is described in Papers II and IV. An important difference between Papers II and Paper IV is that in the latter there has been an important revision of the mathematical foundation, by inclusion of Bayesian updating, regarding how the opening probability is calculated. Paper IV is presented here directly after Paper II to clearly display these differences. Extensive efforts have also been made to collect more input information for the model and these are described separately in Paper III.

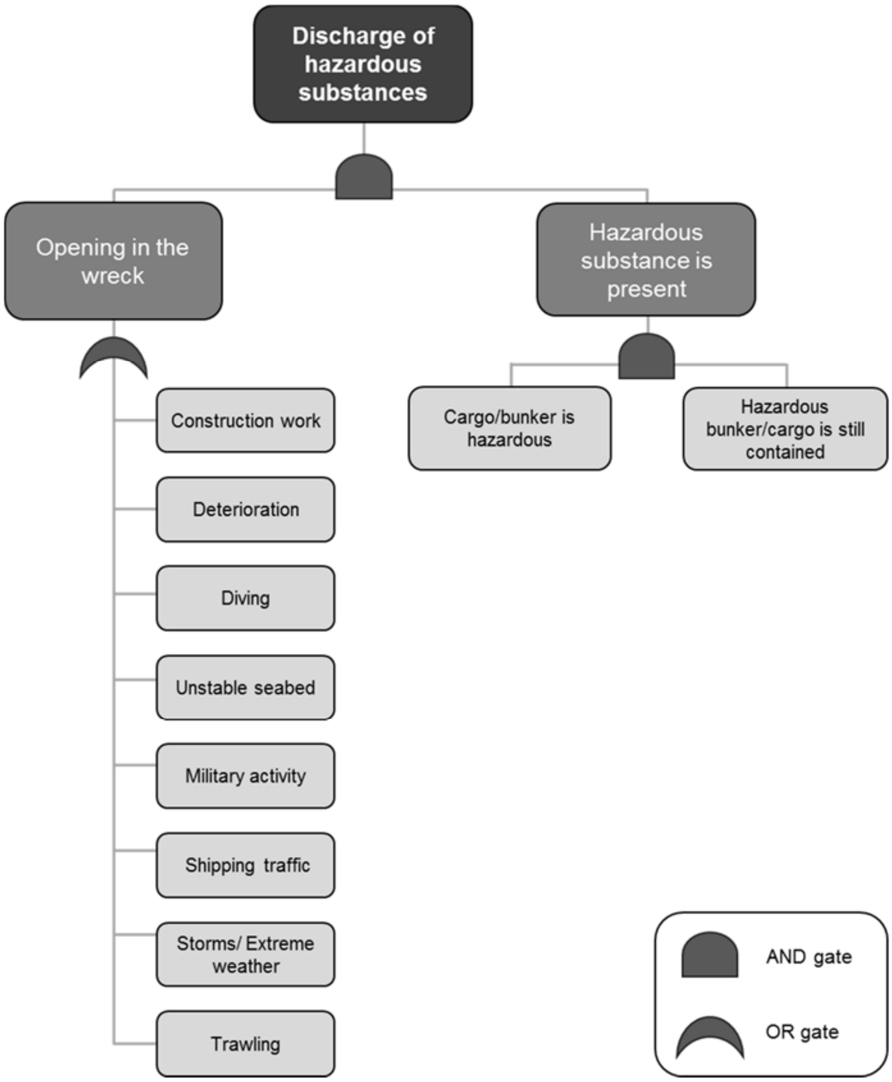

Figure 12. A schematic fault tree structure of VRAKA from Paper III.

6.1.1. A first version of the fault tree model – Paper II

Hazardous activities that are assumed to possibly cause an opening in a shipwreck were identified through a literature review (Etkin et al., 2009; Louzis et al., 2009; Michel et al., 2005; Sender, 2011) and brainstorming sessions with experts. The activities are further described in Section 2.1. A workshop that brought together experts in this field was also held as part of the process of developing the fault tree method. The output from the workshop served as input for further work relating to e.g. the choice of hazardous activities.

Each activity was represented by an intensity, i.e. the frequency of occurrence, and the probability of an opening in the wreck given the occurrence of the activity. An exception was corrosion, which was described directly as the probability of opening since it was assumed to be a continuous process and not of the same nature as the other activities. A generic probability of opening was estimated for each hazardous activity ($P_{opening|acvtivity,i}$) by a group of experts and the risk assessor sets indicator values and estimates of the frequency of the activity ($\lambda_{occurrence,i}$).

Necessary input data were estimated by a group of experts, who were asked to assign the highest reasonable the probability of each activity causing an opening in a shipwreck. To describe the uncertainties of the probability estimations, the values given by the experts were interpreted as the 90th percentile of beta distributions. The percentiles and the estimated parameters they are selected to represent are a way of representing the reliability of the expert judgements. A higher percentile means that the probability of opening is more certain to be lower than the expert judgement. The shape parameter α of the beta distribution was set at a value of 1, implying that the most like value of the probability of an opening is 0. This was estimated to be reasonable, giving that there is currently no information available in Sweden regarding a large discharge of oil from a shipwreck.

Twelve indicators were found to affect the generic probability. These were physical and environmental factors that could influence the deterioration rate and the circumstances in which the activities operated. The indicators were identified through the literature and brainstorming sessions with experts (Louzis et al., 2009; Michel et al., 2005; Etkin et al., 2009; Sender, 2011). The indicators are presented in Chapter 2.1, although in the first version of the fault tree model, the indicators *Maintenance* and *Ship construction* were also included.

In Paper II, a semi-quantitative structure was set up to describe how the twelve indicators affected the probability of opening due to the hazardous activities. The model was initially set at a normal state and the assessor could change this by either decreasing or increasing the robustness of the wreck or environmental prerequisites on a scale from a 'considerably better' to a 'considerably worse' state. In total, five options were available. The magnitude of the change was pre-set in the model. This could be repeated by the assessor for all the indicators and the probability of activities causing an opening was altered with respect to the state of the indicators. With the derived expert information, an expected value, μ_{prior}, was estimated. The assessor information regarding indicators was used to update the beta distributions from μ_{prior} to $\mu_{updated}$. During the updating, the sum of alpha and beta was kept constant, indicating that no new information regarding the uncertainty of the probability estimation was provided.

The probability of an opening as a result of a specific activity was also described by the frequency or rate of occurrence of the activity. This was modelled using gamma distributions and the assessor was provided with fixed intervals.

Furthermore, the assessor estimated the probability that there was a hazardous substance present in the wreck in three steps:

1. Estimation of the probability that there is bunker remaining.
2. Estimation of the probability that there is cargo remaining.
3. Estimation of the probability that the cargo is hazardous.

The assessments regarding the probability of remaining bunker and cargo and whether the cargo was hazardous were performed qualitatively. Possible choices ranged from *Impossible* and *Very low* to *Very high* and *Certain*. It was also possible to set *No information*. Values corresponding to the different classes were set by the authors enabling quantitative description of uncertainties.

The certainty of these assessments from *Low uncertainty* to *High uncertainty* was also estimated. All assessments regarding the volume of bunker and cargo and whether the cargo was environmentally hazardous or not, were made using guiding matrices. The uncertainties of possible choices were represented by beta distributions. The choice of certainty category altered the upper credibility limit. The assessment, for example, would be interpreted as the 85th percentile if the assessor set a high uncertainty and the 95th percentile if uncertainty was set as low.

The amount of hazardous material contained in the wreck was also estimated. A smallest and highest reasonable amount was interpreted as the 10th and 90th percentiles of a lognormal distribution.

6.1.2. The novel fault tree – Paper IV

In Paper IV, a novel fault tree based on the fault tree of Paper II is presented. This fault tree contains the same potentially hazardous activities as the previous fault tree. Each activity is again described in the form of frequency of occurrence and probability of opening. However, the means of calculating the probability of opening differs (Figure 13).

The integration of the effect of site- and wreck-specific indicators on the generic probability of opening is now made by formal Bayesian updating. Furthermore, the simple expert estimations regarding a generic probability of opening in the first fault tree version were replaced by information acquired during an expert elicitation workshop (Paper III). Secondly, the effect of site-specific and wreck-specific indicators on the probability of opening was also estimated by experts at the above-mentioned workshop. This was in contrast to Paper II, where the authors made initial estimations. It should also be noted that the initial estimations were made for another type of structure where the effect of indicators were displayed as deviation from a “normal” wreck-status.

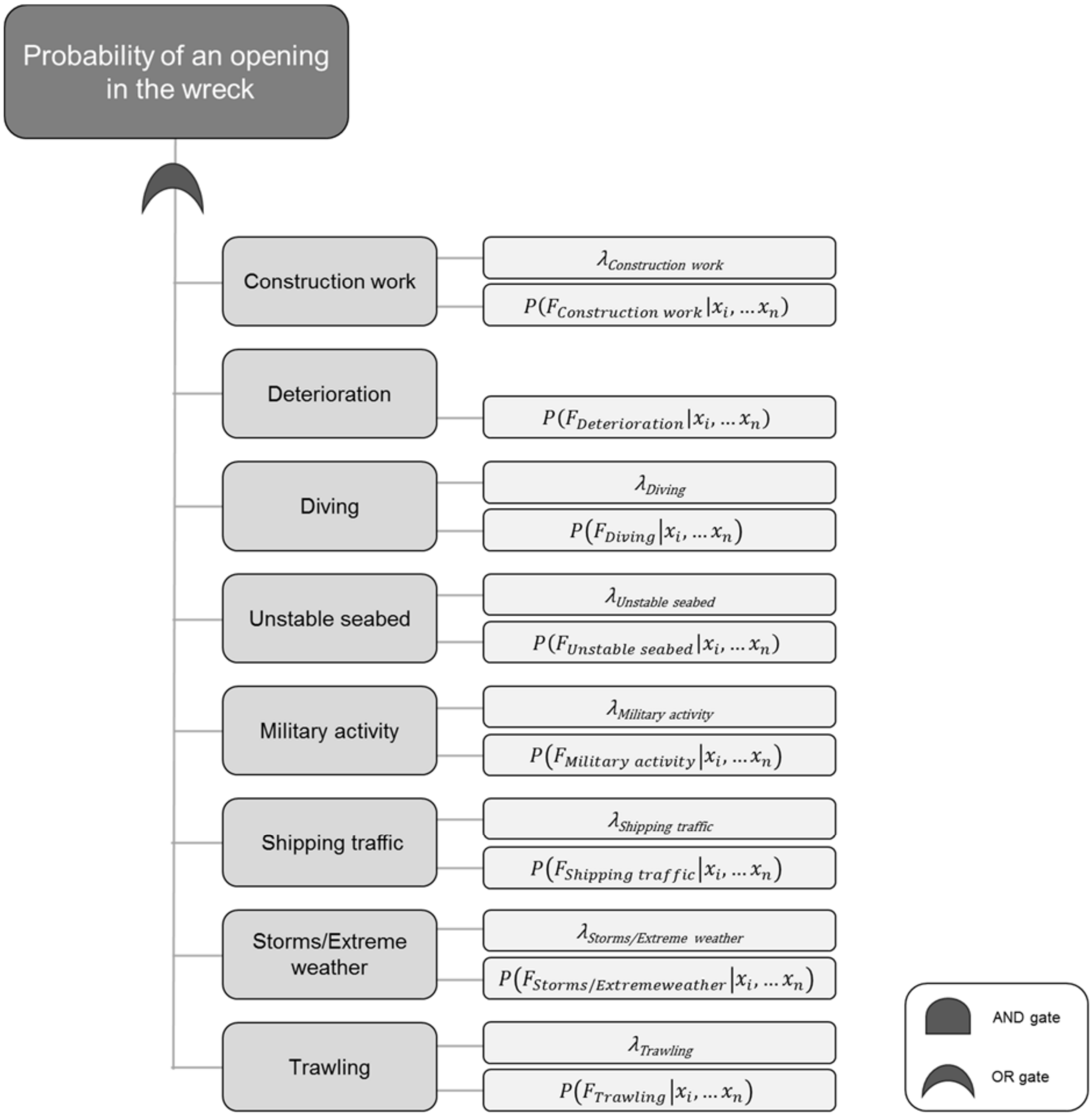

Figure 13. The novel fault tree model for VRAKA according to Paper IV.

For each activity, the effect of the indicators was evaluated and described by means of uncertainty distributions. An assessor can assign values for indicators at the specific site and wreck and only the part of the distribution estimated by experts that is valid for the wreck in question is applied in the model. The prior probability of opening due to an activity, $P(F_j)$, is thus updated based on the status of the site-specific and wreck-specific parameters to a posterior estimation $P(F_j|x_1, \ldots, x_n)$. This facilitates a mathematically correct aggregation of the probability of opening and indicators concerning the specific site and wreck and is enabled by the expert elicitation (Paper III). The model has thus been refined compared to Paper II and now provides probabilistic Bayesian updating incorporating uncertainties through the application of Monte Carlo simulation.

The frequency of hazardous activities is assigned on a continuous scale rather than as a choice of pre-set suggestions as was the case in Paper II. The assessor estimates the lowest reasonable and highest reasonable number of occurrences per year for the activities, that can physically affect the wreck. This is interpreted as the 10th and 90th percentile of a gamma distribution.

The probability that hazardous substances are still contained in the wreck and the probability that the cargo is hazardous and is still contained in the wreck is estimated in the same way as in Paper II. However, in Paper IV, the approach for modelling the uncertainty of these parameters is altered. The probability of the estimated parameter is modelled using a beta distribution where the sum of the shape parameters α and β represents the uncertainty or total information available. Sums are assigned to classes, where a high level of uncertainty is represented by a lower sum of α and β and vice versa. Classes of uncertainty from *Impossible* to *Certain* as well as *No information* are available to the assessor.

6.1.3. Expert elicitation – Paper III

As pointed out in the conclusions in Paper II, the input from experts took the form of rough estimations and there was an apparent need for more robust expert elicitation in order to obtain input for the VRAKA model. A workshop at which more than twenty experts were brought together was held to retrieve necessary input information for the VRAKA model. The workshop was based on the Sheffield Elicitation Framework (SHELF), as described in Section 5.2 (O'Hagan and Oakley, 2010).

Groups for elicitation were formed based on the experts' knowledge. Experts were asked to estimate the probability of a specific activity causing an opening in a shipwreck. Furthermore, estimations were made regarding the state of site-specific and wreck-specific indicators, given that opening and no opening had occurred due to a particular activity. The latter estimations are applied in VRAKA to update the generic probabilities of opening due to different activities and to estimate the joint probability of opening for the wreck in question. The workshop also resulted in two indicators being removed, *Maintenance* and *Ship Construction*, and some combinations of indicators and activities were found to be irrelevant. In Table 3 an overview is provided of which indicators were assumed to have an influence on which activities.

Table 3. Summary of elicited influence or no influence of indicators on activities. Influence is shown as "Y" with a light grey background and no influence as "N" with a dark grey background (Paper III).

Summary of collected data regarding indicators (Data was only elicited where experts found there was a connection).								
	Construct-ion	Diving	Military activity	Deterior-ation	Shipping traffic	Unstable seabed	Storms	Trawling
Average bottom water oxygen concentration	N	N	N	Y	N	N	N	N
Average bottom water salinity	N	N	N	Y	N	N	N	N
Average bottom water temperature	N	N	N	Y	N	N	N	N
Average bottom water current speed	Y	Y	N	Y	N	N	N	N
Ship use	N	N	N	Y	Y	Y	Y	N
Average hull thickness	Y	Y	Y	Y	Y	Y	Y	Y
Seabed character	Y	N	Y	Y	Y	Y	Y	Y
Wreck position on seabed	Y	N	Y	Y	Y	Y	Y	Y
Depth	Y	Y	N	N	Y	Y	Y	Y
Time since sinking	Y	Y	Y	Y	Y	Y	Y	Y

The workshop resulted in 92 probability distributions, representing the uncertainty of the state of indicators in relation to the probability of opening or no opening as a result of each of the hazardous activities. Furthermore, eight distributions were elicited, describing the generic probability of opening due to each of the activities. Examples of distributions are presented in Figure 14, the generic probability of opening due to *Construction work*, and in Figure 15, the uncertainty distribution for *Hull thickness* if an opening has occurred due to shipping traffic.

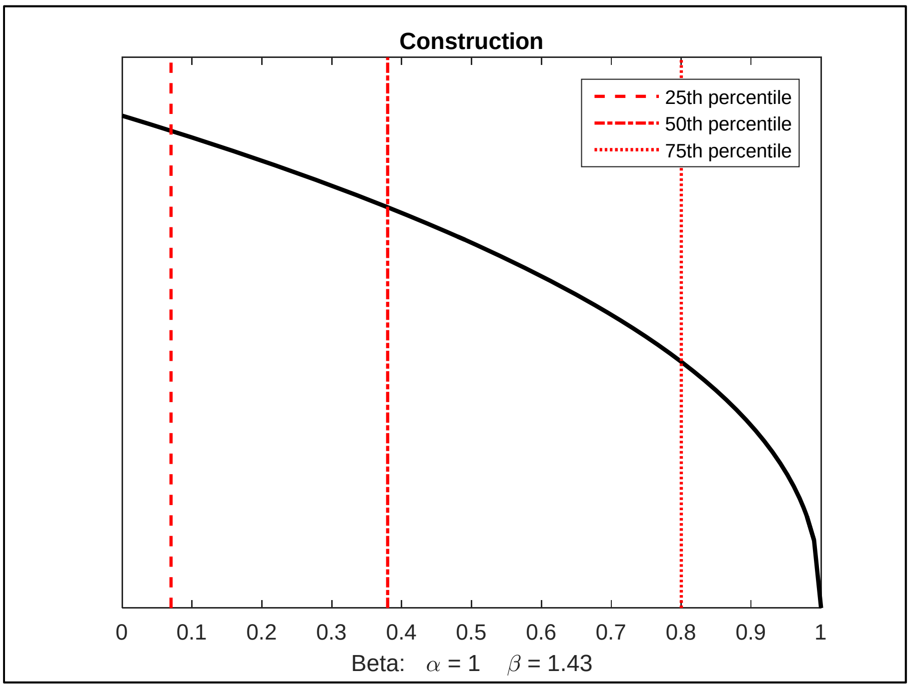

Figure 14. The probability of opening due to construction work.

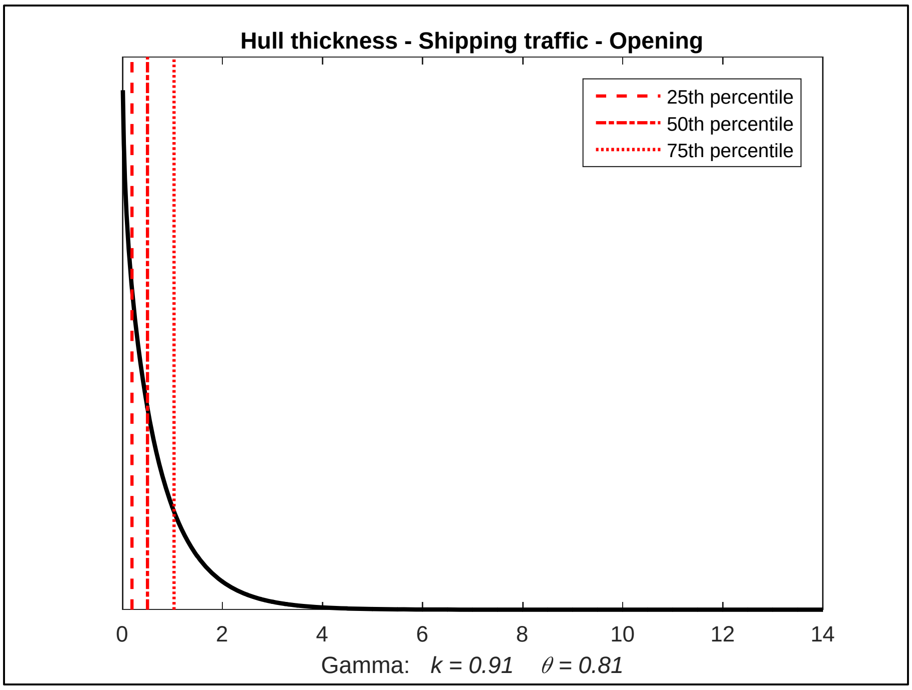

Figure 15. Uncertainty distribution for the Hull thickness indicator, given that an opening has occurred due to Shipping traffic.

6.2. Part 2 – Consequence assessment – Paper V

Estimation of consequences in VRAKA can be performed in three tiers depending on available resources, data and demands regarding the results. In tier 1, risk is described as the expected volume of oil and potential hazardous cargo discharged. Tier 2 applies a matrix combining volume, distance to shore and shoreline sensitivity to estimate the consequence (Table 4). Risk is described as the outcome of the matrix combined with the probability of discharge. Tier 3 is an aggregation of results from Sea Track Web for oil spill trajectory modelling and the Digital Environmental Atlas containing information on shoreline sensitivity to oil spill.

Table 4. Tier 2 Consequence assessment in VRAKA. Based on Kulander et al. (2010) and the DEEPP project (Alcaro et al., 2007) according to Paper III.

	Low severity	**Moderate severity**	**High severity**
Volume	< 10 m^3	10 – 500 m^3	> 500 m^3
Distance to shore	> 10 nautical miles	1 – 10 nautical miles	< 1 nautical mile
Sensitivity	Nearest shore is: Sandy, steep cliffs or rock walls or facilities.	Nearest shore is: Cliff beaches, pebble, boulder or gravel beaches.	Nearest shore is: Reed beds, meadows, fine sediment beaches, or mixed beaches

Having the opportunity to apply consequence assessment in three tiers allows for the possibility of adapting the assessment to the level of ambition and resources available.

However, it should be noted that the selection of a tier will have an impact on the type of results that can be obtained and how these can or should be used. If, for example, tier 1 is applied, the consequences will depend solely on the expected volume of oil discharged. Applying a specific tier thus involves making a decision regarding what the results will encompass.

This reasoning also brings us to a fundamental aspect of risk assessment and management. Developing models and performing risk assessment involves making decisions and choices. Even with the aim of keeping this process free from bias and leaving decisions to the decision-makers and later steps in the risk management process, the developed models and tools will inevitably be coloured by the developers' background and assumptions.

6.3. Part 3 – Risk Evaluation in VRAKA

Results from VRAKA can be used to compare wrecks and for deciding which wrecks warrant action. The estimated risk can be compared as a measure itself (tier 1) or the two components – probability of discharge and the consequences – can be compared separately (all tiers). If several wrecks are within a close distance, such groups can also be compared to other groups since combined probabilities and consequences can produce other results. Furthermore, remediation costs could perhaps be lowered by coordinating operations.

In the case of risk evaluation, i.e. *making risk tolerability decisions* and *analysing options*, no specific component of VRAKA is applicable. Deciding on risk criteria and what risk is tolerable is up to the assessor or decision-maker. However, the main benefit of VRAKA is that it can be applied to estimate the relative risk between wrecks and priorities mitigation measures to evaluate the risk reduction options.

In simple terms, risk reduction can be achieved by either decreasing the probability of an activity or reducing the consequences. VRAKA can for example be used to analyse a change in the probability of discharge of hazardous substances by reducing the frequency of a hazardous activity and comparing the risk related to the current frequency of the activity with a reduced frequency.

6.4. A tool for applying VRAKA

VRAKA has also been realised in the form of an Excel-based tool. It includes two files containing a number of sheets that guide the assessor through the risk estimation (Figure 16). Hereafter follows a brief overview of the tool. Further description is provided in Appendix A1.

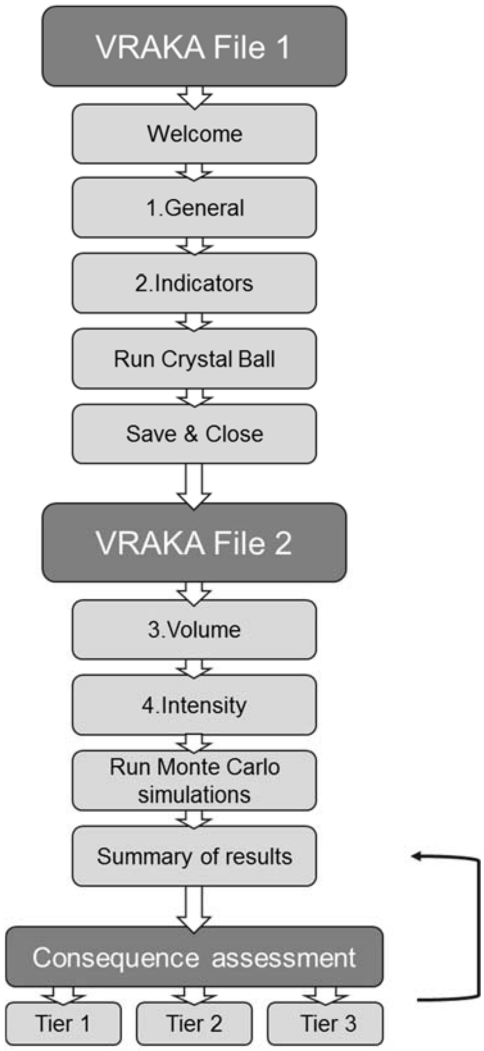

Figure 16. Schematic view of the tool for applying VRAKA (VRAKA, Probabilistic risk assessment of shipwrecks, Handbook. Version Oct. 2016).

Figure 17 shows the structure of VRAKA in Excel. The purpose of a more detailed presentation is to clarify how uncertainties are included in the risk estimation. VRAKA is separated into two files due to practicalities relating to Crystal Ball. The calculations in file one should be performed before the calculations in file two. The former serves as input to the latter and thus cannot be performed simultaneously. File 1 contains information from the expert elicitation regarding site-specific and wreck-specific parameters. This is updated based on the values for the wreck in question assigned by the user of VRAKA. In the second file, all the remaining calculations and simulations are performed. The consequence of this separation is that sensitivity analysis will need to be performed in two steps.

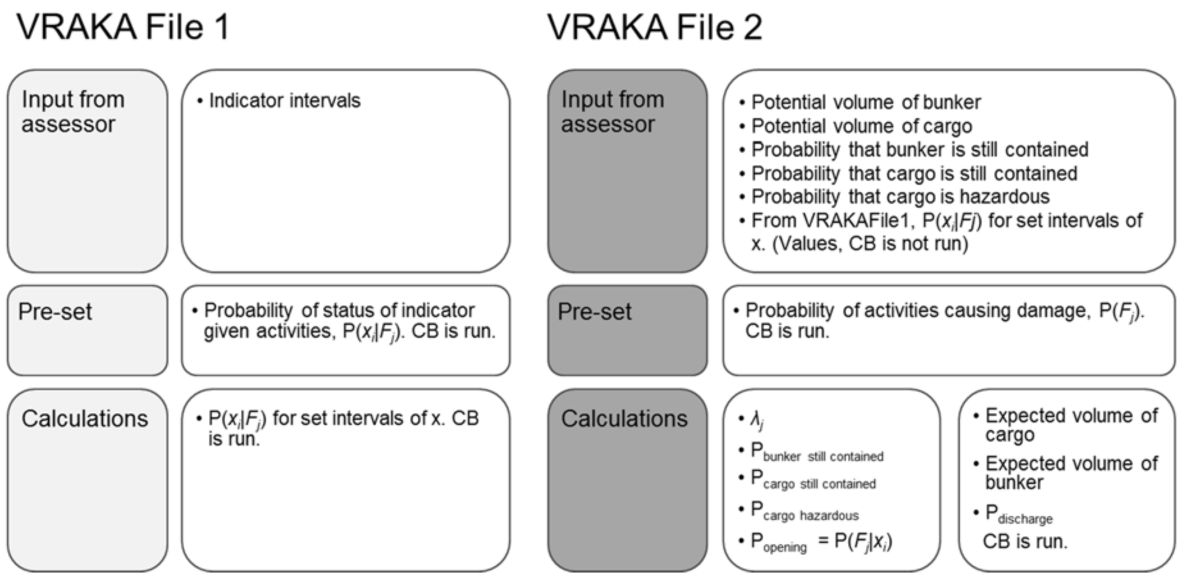

Figure 17. The structure of VRAKA in the Excel-based tool. CB is an abbreviation of Crystal Ball, an add-in software for Monte Carlo simulations.

7. Discussion

Potentially polluting shipwrecks are a growing environmental threat and adequate decision support is needed to cope with the problem. The risk from shipwrecks is influenced by numerous and uncertain variables and the interaction of these variables is a truly complex matter. Data are typically lacking and gathering further information could be costly or, for various other reasons, difficult to achieve. Handling of these uncertainties is necessary in order to obtain proper risk assessment results and decision support. This thesis initially identified a need for further research on risk assessment of shipwrecks. A framework for structuring and guiding development as well as risk management was then suggested and a model for risk assessment of wrecks (VRAKA) was developed as an integral part of the framework. VRAKA can be applied to prioritise mitigation measures and resource allocation for potentially polluting shipwrecks based on scientifically well-founded input acquired through probabilistic risk assessment.

7.1. A generic framework

The framework was developed based on a comparison of identified methods and approaches currently applied to shipwrecks (Paper I). It was shown that at the time of the study there was no comprehensive method for shipwrecks and none that facilitated a quantitative assessment. The analysis was further developed in Chapter 3 of this thesis, which include additional, recently developed approaches. It was concluded that consequence assessment is now in general more solid but there is no fully probabilistic approach that takes uncertainties into account. The suggested framework stresses the link between risk assessment and decision-making and presents a holistic structure based on well-established views of risk management. Hence, the framework argues in favour of a proactive approach.

7.2. VRAKA – a comprehensive model

Due to the complex nature of the risks posed by shipwrecks and the inherent uncertainties, it is crucial to apply a structured and probabilistic approach. The VRAKA model therefore comprises a probabilistic method, with explicit handling of uncertainties, for estimating the probability of discharge and an aggregation of methods for estimating the consequences.

7.2.1. A fault tree method

Several methods for logical modelling exists. The fault three was chosen due to its possibility to provide structure and transparency to the problem. Furthermore, the mathematical framework suits the conceptual model of VRAKA and probabilistic risk assessment of shipwrecks well. Applying a probabilistic approach allows uncertainties to be taken into account in input data and results. In VRAKA, a fault tree was developed and applied to calculate the probability of discharge of hazardous substances. The fault tree combines the probability of an opening occurring in the wreck with the probability that there is hazardous material inside the wreck. Statistical distributions describe the uncertainties of input data and through the use of Monte Carlo simulation the uncertainties of the results can be calculated and displayed.

A probabilistic approach also allows for sensitivity and uncertainty analysis. Uncertainty analysis facilitates an explicit representation of uncertainties in input data and their effects on the model outputs. Sensitivity analysis makes it possible to identify which input variables contribute most to output uncertainty, and thus provides guidance on determining which additional information should be prioritised in order to achieve more reliable risk calculations. The user of VRAKA can also run different scenarios in order to see how the risk is affected and thus evaluate possible measure for reducing the risk.

7.2.2. Consequence assessment

Depending on the purpose of the risk assessment and available resources, VRAKA makes possible the selection of a relevant tier for making a consequence assessment. VRAKA offers three tiers of increasing refinement: a first tier where the amount of oil serves as a proxy for consequences, a second tier where a sensitivity matrix is applied to describe the consequences (the matrix contains the volume of oil, distance to shore and the sensitivity of the specific shore type, i.e. a semi-quantitative consequence assessment.), and a third tier where an oil spill trajectory tool is combined with sensitivity mapping of the coast. Uncertainties can be taken into account to some extent in the latter two since the set values in the sensitivity matrix are provided as an interval and the oil spill trajectory tool can be run for several scenarios. Currently, none of the tiers provided offers a consequence assessment from a social or economic point of view, which are of course are crucial areas when making an assessment to find sustainable solutions. All the tiers can however at present offer an estimation of the consequences off a potential discharge of oil that can serve as input for decision-making. The consequence assessment of VRAKA can be applied to compare shipwrecks independent of selection of tier possible.

7.2.3. Risk estimation

A major focus of this work was to develop a model to estimate the probability of discharge of oil and to illustrate how this estimation can be combined with different types of consequence assessments. Hence, to estimate the risk posed by potentially polluting shipwrecks.

In this thesis risk is defined as a combination of probability and consequences. However, different means for combining probability and consequences are applied when estimating the level of risk. The choice of how to present the risk will depend on the aims of the risk assessment. Risk can, as in tier 1, be estimated as the expected value of the discharged volume of hazardous substance. Using this approach, the user must be aware of the fact that very significant consequences can be obscured by a small probability or vice versa as mentioned in Chapter 2. It is thus important to be aware of the limitations in this way of expressing the risk. A separate analysis of the probability, the consequences, and the combined risk estimate will provide a more holistic picture of the risk.

Tiers 2 and 3 inherently encourage the assessor to evaluate the probability of discharge and the consequences separately by not providing actual numbers representing the consequences. The assessor thus weighs the estimations of consequences in relation to the probability of discharge. The choice of tier for the consequence assessment will also involve selecting the types of consequences to be included. An assessor must always be aware of and take into account how the choice of risk definition and the description of the consequences will affect the outcome of the risk estimation when making the final decision.

7.2.4. Risk evaluation

There are no regulations or criteria specifying when a wreck is a threat to the marine environment to the extent that measures should be taken, unless a larger discharge is underway. The role of the decision-maker is therefore very important and the risk evaluation and comparison of wrecks imperative for supporting decision regarding mitigation measures. VRAKA can be applied to prioritise mitigation measures by analysis of potential risk-mitigation options. For example, by analysing the effect on results of decreasing or banning shipping traffic in the area.

Risk mitigation measures in terms of reduced risk level could also be evaluated in relation to the cost for such mitigation using e.g. cost-benefit analysis, thus implying that risk mitigation must also be valued in economic terms. The cost of achieving specific risk levels can also be evaluated by cost effectiveness analysis, in order to find which alternative that would reach a specific risk criterion, or goal, to the lowest cost. Another example is multi criteria decision analysis, which takes a number of criteria into account.

It is the responsibility of the decision-maker to, based on e.g. information retrieved by VRAKA, decide what the most desirable option is. For example, the largest risk reduction to the lowest cost or simply a reduction of the largest risk? There are several alternatives that are relevant from different perspectives. Although, VRAKA can provide support and input for a decision-making process in different ways, it is up to the decision maker to set the goals for the assessment and choose the proper way, e.g. the relevant tier, for the type of decision at hand.

7.3. Expert elicitation

Information is scarce on shipwreck conditions and data derived by expert elicitation is essential for probabilistic risk assessment of shipwrecks. Input for the fault tree in VRAKA was derived by means of a rigorous expert elicitation process where experts were asked to provide their subjective beliefs about relevant quantities such as the probability of an opening in a shipwreck du to hazardous activities and the influence of site-specific and wreck-specific indicators on that probability.

A total of 23 experts from various areas of expertise participated in the elicitation. An ideal situation would have involved more experts to embody a wider common level of competence in all the groups. Certain experts were included in several groups for some of the elicitations, but arranging for all areas of knowledge to be represented for all issues was not possible with respect to the time available. Although efforts were made to invite a large number of experts, it was not possible at the time and for the chosen structure of the elicitation to attract further expertise. An alternative could have been to run several workshops with fewer experts on each occasion.

Probabilistic risk assessment of shipwrecks would be extremely difficult if not impossible if expert elicitation was not performed. Although the task was difficult, it is important to bear in mind that expert knowledge is not expressed in terms of precise values and that uncertainties were also taken into account.

7.4. Validation of VRAKA

Validation in absolute terms of a model such as VRAKA is not feasible since the process modelled cannot be controlled and is not possible to follow up. Such action would include finding a large number of wrecks and study them for a very long period of time in order to obtain statistically valid results. However, what can be done is to test real and hypothetical wrecks and to analyse changes in input data in relation to changes in results.

VRAKA has been tested on several hypothetical and real shipwrecks. Results show how VRAKA can be applied to estimate the risk from shipwrecks in terms of types of results and how uncertainty and sensitivity analysis can be performed.

7.5. Outlook

The problem of potentially hazardous shipwrecks is complex. Numerous authorities, companies, universities and experts are involved. The Swedish coastguard will act if oil is found on beaches or on the water surface, the Swedish Maritime Administration will remove wrecks if they pose a threat to shipping traffic while the Swedish Agency for Marine and Water Management has overall responsibility. For a risk management process to be efficient, these organisations will have to cooperate. Data for risk assessment will have to be shared as well as the requisite knowledge and competence for an effective risk reduction and control. The stakeholders involved might also have different interests and views about when a risk is unacceptable and how it should be dealt with.

VRAKA has been operationalised in an Excel-based tool to facilitate risk assessment of shipwrecks for the authority responsible. Using VRAKA requires knowledge of where to find the information required in the tool, which is why an interdisciplinary approach is important. It could be argued that "the assessor" rather should be a team in order to facilitate assessment since many different aspects need to be considered. It is also essential to understand the connection between the quality and type of input data, the choice of tier for consequence assessment, i.e. how risk is expressed, and what the results will include and represent. Results should never be considered as merely numbers but rather analysed bearing in mind the process of the assessment. Results will also need to be weighed against other information in order to be able to fully weight costs against benefits of mitigation measures and to make an informed decision.

Many assumptions have been made during the course of development. As stated in Section 6.2, models and tools cannot be entirely free of bias and the influence of the model constructors. To cope with this notion, several experts have been involved in the process at numerous occasions. A reference group has been in place throughout the process and experts groups varying in size have contributed informally and formally to the development.

VRAKA has been developed in cooperation with, among, others the Swedish Maritime Administration and the Swedish Agency for Marine and Water Management. Discussions are about to get under way regarding the use of VRAKA for risk estimation on a national level.

7.6. Suggestions for further research.

Based on the work carried out within this thesis, the following are identified as possible areas for further research:

- The estimation of consequences in tiers 2 and 3 is semi-quantitative. To further encompass associated uncertainties, a probabilistic approach could be adopted. An example of such a method is SIMAP (McCay et al., 2004), which provides probabilistic estimates of consequences. Initial studies linking VRAKA to the SIMAP method has been performed (Etkin et al., In prep).

- The Swedish Meteorological and Hydrological Institute is developing Seatrack Web for broader analysis where the assessor can model a spill released on several occasions and obtain probability maps of where the oil might be deposited. This is another possibility for probabilistic assessment of consequences in future versions of VRAKA.

- An interesting development of VRAKA would be to refine the estimation of environmental consequences and also provide means for analysing further aspects such as the season during which the spill occurred or specific endangered animals potentially affected by a spill. It would also be profitable to include further socioeconomic aspects in the consequence assessment.

- In general, the main focus of oil spills is on large acute spills. Small and more continuous spills are acknowledged less frequently. However, it has been shown by e.g. Lindgren et al. (2012) that small inputs, resulting in low concentrations of oil, also have a negative effect on microbial and meiofaunal communities. Improving the possibility of estimating consequences of small discharges could therefore be considered in a future development of VRAKA.

- At present VRAKA can be applied to evaluate the relative risks from shipwrecks. A possible further development could be to link VRAKA to tools for more advanced risk evaluation. For example, performing a cost-benefit analysis can display the benefit of mitigating the risk by providing information on the societal profitability (net benefit) of risk mitigation measures. Multi criteria decision analysis would facilitate a more comprehensive sustainability analysis, taking into account local social, environmental and economic effects that are difficult or not possible to take into account in cost-benefit analysis.

- Model development and risk assessment of potentially polluting shipwrecks is ongoing in several other countries. There are many possibilities for collaboration. Expert elicitation was performed with a focus on the Swedish wreck population. However, the structure of the VRAKA model is generic and it could be applied internationally.

- The method and tool for probabilistic risk estimation of shipwrecks could, for validation purposes, be further tested and calibrated. There are more than 300 wrecks in Scandinavian waters that the Swedish Maritime Administration (2011) suggests may pose a threat to the marine environment. A selection of well-known wrecks for which in-situ inspection can be performed would be suitable to use in order to test and validate the model (see e.g. Hassellöv et al., 2014; Hassellöv et al., 2015).

8. Conclusions

The following main conclusions have been reached from this thesis work:

- *There is a need for a comprehensive risk assessment approach for shipwrecks.*
  There is a lack of methods for comprehensive and quantitative risk assessment of shipwrecks. Specifically, methods for estimating the probability of discharge and for including uncertainty analysis of the risk estimation are lacking.

- *A framework for risk management of shipwrecks is suggested.*
  This thesis presents a generic framework for risk management of shipwrecks in accordance with the ISO standard for risk management that offers a structure and support for developing risk assessment models, and provides guidance for shipwreck-related risk management.

- *Novel input data is derived for risk assessment of shipwrecks.*
  Expert elicitation was used to address the intrinsic uncertainties of risk assessment of shipwrecks. The information obtained has not previously been available and is a prerequisite for quantitative risk assessment of shipwrecks. The information provides an essential foundation that can be updated using site- and wreck-specific preconditions as a basis. It is now possible to estimate the probability of discharge from potentially polluting shipwrecks and to incorporate uncertainties that influence the risk.

- *VRAKA – a model for comprehensive risk assessment of shipwrecks.*
  The developed model takes into account both the probability of discharge and its potential consequences. Risk evaluation can also be performed based on the results from VRAKA. The risk assessment model is implemented in a spreadsheet tool (Microsoft Excel) to facilitate application.

  - *A method for estimating the probability of hazardous discharge.*
    The method enables estimation of the annual probability of discharge of hazardous substances from shipwrecks. Bayesian updating of a generic probability of opening in a wreck is performed based on influence of wreck- and site-specific indicators. The Bayesian approach enables a formal integration of expert judgement regarding potential hazards of different activities with available data on the occurrence and intensity (frequency) of such activities. The logical structure of the method and the type of input

information combined with Monte Carlo simulations enables uncertainty and sensitivity analyses to be made of the results.

- *An approach for estimating the consequences of a potential discharge.*
  In VRAKA, consequences can be estimated in three tiers depending on available resources and, data and the aim of the risk assessment.

- *Application and validation of VRAKA.*
  VRAKA has been applied to a number of hypothetical and real shipwrecks. This study provides important knowledge concerning changes of results in relation to input data also coupled to the uncertainty distributions of input data. The application showed that results of the probability of opening spanning over at least two orders of magnitude is possible.

VRAKA is a comprehensive, structured, quantitative risk assessment model for shipwrecks that takes uncertainties into account. For the very first time, the probability of discharge can be quantified and combined with the consequences of such a discharge to form a quantitative risk estimation for a particular shipwreck. A number of factors affecting the risk posed by shipwrecks have been identified and are included in the assessment. The structured quantitative model also implies that risk assessment can be performed consistently for all the wrecks studied.

The framework and model developed facilitates adequate and transparent risk assessment for shipwrecks, thus providing support for reaching well-informed decisions regarding prioritisation and mitigation measures for potentially polluting wrecks. This in turn facilitates more cost efficient risk mitigation and efficient resource allocation to counter this environmental threat.

9. References

ALCARO, L., AMATO, E., CABIOCH, F., FARCHI, C. & GOURIOU, V. 2007. DEEPP Project, DEvelopment of European guidelines for Potentially Polluting shipwrecks. ICRAM, Instituto Centrale per la Ricerca scientifica e tecnologica Applicata al Mare, CEDRE, CEntre de Documentation de Recherché et d'Epérimentations sur les pollutions accidentelles des eaux.

AVEN, T. 2003. *Foundations of risk analysis, a knowledge and decision-oriented perspective,* West Sussex, England, John Wiley & Sons Ltd.

AVEN, T. 2010. On how to define, understand and describe risk. *Reliability Engineering & System Safety,* 95**,** 623-631.

AVEN, T. 2012. Foundations of Risk Analysis. Wiley. ProQuest Ebook Central [2 september 2016].

AVEN, T., BEN-HAIM, Y., ANDERSEN BOJE, H., COX, T., LÓPEZ DROGUETT, E., GUIKEMA, S., KROEGER, W., RENN, O., THOMPSON, K. M. & ZIO, E. 2015. SRA glossary. The Society For Risk Analysis.

AVEN, T. & RENN, O. 2009. On risk defined as an event where the outcome is uncertain. *Journal of Risk Research,* 12**,** 1-11.

AYYUB, B. 2001. *Elicitation of Expert Opinions for Uncertainty and Risks,* The United States of America, CRC Press LCC.

BEDFORD, T. & COOKE, R. 2001. *Probabilistic risk analysis. Foundations and methods,* United States of America, Cambridge University Press.

BERNSTEIN, P. L. 1996. *Against the gods. The remarkable story of risk.,* USA, John Wiley and sons, INC.

BURGMAN, M. 2005. *Risk and decisions for conservation and environmental management,* New York, Cambridge university press.

COOKE, R. M. 1991. *Experts in Uncertainty : Opinion and Subjective Probability in Science*, Oxford University Press.

COOKE, R. M. & GOOSSENS, L. H. J. 2000. Procedures guide for structured expert judgement in accident consequence modelling. *Radiation Protection Dosimetry,* 90**,** 303-309.

COUNTY ADMINISTRATIVE BOARD OF VÄSTRA GÖTALAND. 2015. *Digital Miljöatlas* [Online]. Available: http://www.lansstyrelsen.se/vastragotaland/Sv/manniska-och-samhalle/krisberedskap/skydd-mot-olyckor/Pages/digital-miljoatals.aspx [Accessed 30 October 2015].

ETKIN, D., FRENCH MCCAY, D., HORN, M., LANDQUIST, H., HASSELLÖV, I. M. & WOLFORD, A. J. In prep. Quantification of Oil Spill Risk. *In:* FINGAS, M. (ed.) *Oil Spill Science and Technology.* Burlington, USA: Elsevier.

ETKIN, D., VAN ROOIJ, H. & FRENCH-MCCAY, D. 2009. Risk assessment modeling approach for the prioritization of oil removal operations from sunken wrecks. *Effects of oil on wildlife.* Tallin, Estonia.

FEJES, J., COLE, S. & HASSELSTRÖM, L. 2011. The REMEDE Project: A useful framework for assessing non-market damages from oil spills? : Department of Economics, Umeå Universitet.

GARTHWAITE, P. H., KADANE, J. B. & O'HAGAN, A. 2005. Statistical methods for eliciting probability distributions. *Journal of the American Statistical Association,* 100**,** 680-700.

GLICKEN, J. 2000. Getting stakeholder participation 'right': a discussion of participatory processes and possible pitfalls. *Environmental Science & Policy,* 3**,** 305-310.

HACKING, I. 2001. *An introduction to probability and inductive logic.,* The United States of America, Cambridge University Press.

HANLEY, N. & BARBIER, E. B. 2009. *Pricing nature. Cost-Benefit Analysis and Environmental Policy.,* UK, Edward Elgar Publishing Limited.

HASSELLÖV, I. M., OLSSON, U., EKBERG, G., ÖSTIN, A., SIMONSSON, F., LARSSON, C., LANDQUIST, H., LINDGREN, J. F., LINDHE, A., ROSÉN, L. & TENGBERG, A. 2015. Environmental risks posed by shipwrecks II. In Swedish: Miljörisker sjunkna vrak II. Undersökningsmetoder och miljöaspekter. . Sjöfartsverket.

HASSELLÖV, I. M., OLSSON, U., EKBERG, G., ÖSTIN, A., SIMONSSON, F., LARSSON, C., SENDER, U., LANDQUIST, H., LINDGREN, J. F., LINDHE, A. & ROSÉN, L. 2014. Environmental risks posed by shipwrecks. In Swedish: Miljörisker sjunkna vrak. Undersökningsmetoder och miljöaspekter. . *In:* ADMINISTRATION)., S. T. S. M. (ed.).

HORA, S. C. & VON WINTERFELDT, D. 1997. Nuclear waste and future societies: A look into the deep future. *Technological Forecasting and Social Change,* 56**,** 155-170.

IDAAS, K. 2005. Norwegian Pollution control authority work on shipwreck,. *2005 International Oil Spill Conference, IOSC 2005.* Miami Beach, FL,.

IEC 1995. Dependability Management - Part 3: Application guide - Section 9: Risk analysis of technological systems. International Electrotechnical Commission.

INTERNATIONAL MARITIME ORGANISATION 2002. Guidelines for Formal Sadety Assessment (FSA) for use in the IMO rule-making process. London.

INTERNATIONAL MARITIME ORGANIZATION 2007. Nairobi International Convention on the Remval of Wrecks. *In:* INTERNATIONAL MARITIME ORGANIZATION (ed.) *LEG/CONF.16/19.*

ISO 2009. Risk management - Principles and guidelines, ISO 31000:2009(E). Geneva: International Organization for Standardization.

JENKINSON, D. 2005. The elicitation of probabilities: A review of the statistical literature. Citeseer.

JONES-LEE, M. & AVEN, T. 2011. ALARP—What does it really mean? *Reliability Engineering & System Safety,* 96**,** 877-882.

KAPLAN, S. & GARRICK, J. 1981. On the quantitative definition of risk. *Risk Analysis,* Vol. 1.

KINGSTON, P. F. 2002. Long-term environmental impact of oil spills. *Spill science & Technology bulletin,* 7**,** 53-61.

KIUREGHIAN, A. D. & DITLEVSEN, O. 2009. Aleatory or epistemic? Does it matter? *Structural Safety,* 31**,** 105-112.

KUHNERT, P. M., MARTIN, T. G. & GRIFFITHS, S. P. 2010. A guide to eliciting and using expert knowledge in Bayesian ecological models. *Ecology Letters,* 13**,** 900-914.

KULANDER, K. E., ERICSSON, M., TEGENACK, A., FEJES, J. & EVANS, S. 2010. Saneringsmanual för olja på svenska stränder.

LARSSON, B.-Å., EKBERG, G., SÖDERBERG, M. & JESÄTER, M. 2011. Miljörisker från fartygsvrak. The Swedish Maritime Administration,.

LINDGREN, J. F. 2015. *Evaluating effects of low concentrations of oil in marine benthic communities.* Doctoral thesis, Chalmers University of Technology.

LINDGREN, J. F., HASSELLÖV, I. M. & DAHLLÖF, I. 2012. Meiofaunal and bacterial community response to diesel additions in a microcosm study. *Mar Poll Bull.* **,** 595-601.

LIUNGMAN, O. & MATTSON, J. 2011. Scientific Documentation of Seatrack Web; physical processes, algorithms and references. *In:* SMHI (ed.).

LOUZIS, K., KOIMTZOGLOU, A. & VENTIKOS, N. P. The Risk of Wrecks or the Wreck of Risk? The Greek Paradigm. 2nd International Conference on Risk Analysis and Crisis Reponse, 2009 Beijing, China. Atlantis Press.

MCCAY, D. F., ROWE, J. J., WHITTIER, N., SANKARANARAYANAN, S. & ETKIN, D. S. 2004. Estimation of potential impacts and natural resource damages of oil. *Journal of Hazardous Materials,* 107**,** 11-25.

METZ, B., DAVIDSON, O., BOSCH, P., DAVE, R. & MEYER, L. 2007. Mitigation of climate change. IPCC.

MEYER, M. & BOOKER, J. 2001. *Eliciting and Analyzing Expert Judgment*, Society for Industrial and Applied Mathematics.

MICHEL, J., GILBERT, T., WALDRON, J., BLOCKSIDGE, C. T., SCHMIDT ETKIN, D. & URBAN, R. 2005. Potentially polluting wrecks in marine waters. *International oil spill conference.*

MORGAN, G. M. & HENRION, M. 1990. *Uncertainty. A guide to dealing with uncertainty in quantiative risk and policy analysis.,* The United States of America, Cambridge university press.

MUNIER, N. 2004. *Multicriteria Environmental Assessmen. A practical guide.,* Dordrecht, Kluwer Academic Publishers.

NOAA 2009. Wreck Oil Removal Program (WORP) 2009 Demonstration Project Overview. National Oceanic and Athmospheric Administration,.

NOAA 2013. Risk Assessment for Potentially Polluting Wrecks in U.S. Waters. Silver Spring, MD: National Oceanic and Atmospheric Administration.

O'HAGAN, A., BUCK, C. E., DANESHKHAH, A., EISER, R. J., GARTHWAITE, P. H., JENKINSON, D. J., OAKLEY, J. F. & RAKOW, T. 2006. *Uncertain Judgements: Eliciting Experts' Probabilities,* Chichester, England., Johan Wiley & Sons Ltd.

O'HAGAN, A. & OAKLEY, J. E. 2004. Probability is perfect, but we can't elicit it perfectly. *Reliability Engineering & System Safety,* 85**,** 239-248.

O'HAGAN, A. & OAKLEY, J. F. 2010. The Sheffield Elicitation Framework (SHELF, v2.0). An "Off the Shelf" package for eliciting probability distributions. Department of Probability and Statistics. The University of Sheffield. UK. (http://www.tonyohagan.co.uk/shelf/).

PHILLIPS, L. D. 1999. Group Elicitation of Probability Distributions: Are Many Heads Better Than One? *In:* SHANTEAU, J., MELLERS, B. A. & SCHUM, D. A. (eds.) *Decision Science and Technology: Reflections on the Contributions of Ward Edwards.* Boston, MA: Springer US.

ROBERTS, N. H., VESLEY, W. E., HAASL, D. F. & GOLDBERG, F. F. 1981. *Fault tree handbook,* Washington, D.C., Systems and Reliability Research, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission.

SENDER, U. 2011. Korrosion på skeppsvrak i svenska vatten. (Corrosion of shipwrecks in Swedish waters). Swerea KIMAB.

SMHI. 2011. *Seatrack Web* [Online]. The Swedish Meteorological and Hydrological Institute. Available: https://stw.smhi.se/ [Accessed 2016-02-24 2016].

SMHI. 2015. *Seatrack web - Spridningsprognoser för oljeutsläpp och andra föroreningar* [Online]. The Swedish Meteorological and Hydrological Institute. Available: http://www.smhi.se/professionella-tjanster/professionella-tjanster/sakerhet-och-beredskap/seatrack-web-spridningsprognoser-for-oljeutslapp-och-andra-fororeningar-1.1646 [Accessed 2016-02-29 2016].

SPREP & SOPAC. A regional strategy to address marine pollution from world war II wrecks. 13th SPREP Meeting, 2002 Majuro, Marhsall Islands. The Pacific Ocean Pollution Prevention Programme, PACPOL.

SUTER, G. W. 2007. *Ecological risk assessment,* Florida, CRC Press. Taylor and Francis Group.

TVERSKY, A. & KAHNEMAN, D. 1974. Judgment under uncertainty: heuristics and biases. Biases in judgments reveal some heuristics of thinking under uncertainty. *Science,* 185**,** 1124-1131.

TVERSKY, A. & KAHNEMAN, D. 1983. Extensional versus intuitive reasoning: The conjunction fallacy in probability judgment. *Psychological Review,* 90**,** 293-315.

WALLS, L. & QUIGLEY, J. 2001. Building prior distributions to support Bayesian reliability growth modelling using expert judgement. *Reliability Engineering & System Safety,* 74**,** 117-128.

VENTIKOS, N. P., LOUZIS, K. & KOIMTZOGLOU, A. 2013. The Shipwrecks in Greece are Going Fuzzy: A Study for the Potential of Oil Pollution from Shipwrecks in Greek Waters. *Human and Ecological Risk Assessment,* 19**,** 462-491.

VENTIKOS, N. P., LOUZIS, K., KOIMTZOGLOU, A. & DELIKANIDIS, P. 2016. Enhanced Decision Making through Probabilistic Shipwreck Risk Assessment: Focusing on the Situation in Greece. *Frontiers in Marine Science,* 3.

VILLEJOUBERT, G. & MANDEL, D. R. 2002. The inverse fallacy: An account of deviations from Bayes's theorem and the additivity principle. *Memory & Cognition,* 30**,** 171-178.

WRIGHT, G., COUDERT, F., BENTLEY, M., DEVILLE, S. & STEEL, G. 2014. *This Study is Intentionally Left Blank - A systematic literature review of blank pages in academic publishing*.