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Strategies for Protection of Wooden Underwater Cultural Heritage in the Baltic Sea Against Marine Borers. The EU Project 'WreckProtect'

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Marine borers constitute a great danger to historical shipwreck in marine environments as they are able to decompose wood material in just a few years. Recently, there have been indications that the marine borer *Teredo navalis* is spreading into the brackish Baltic sea, where thousands of invaluable historical wrecks for centuries have had unique preservation conditions. The WreckProtect project was a coordination and support action funded by the European Commission within the 7th Framework Program. The main objective of the project was to develop tools for predicting the spread of marine borers into the Baltic and to evaluate methods for *in situ* protection of the historical wreck and submerged settlements. This paper gives a summary final report of the project and an overview of results.

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Introduction

Today the Baltic Sea is a unique resource for marine archaeology. The low salinity (5–10 practical salinity units (PSU)) of the water has excluded aggressive marine borers, and historical shipwrecks can be found intact both above and beneath the seabed. The Vasa ship, the number one tourist attraction of Stockholm, Sweden, is an example of the unique preservation conditions in the Baltic Sea (Figure 1). It is estimated that around 100,000 shipwrecks are present in the Baltic today and at least 6000 are of high archaeological importance (Olsson, 2006). The nine countries that surround the Baltic — Denmark, Sweden, Germany, Poland, Finland, Estonia, Latvia, Lithuania and Russia — discover new wrecks each year and consequently the number of wrecks is still rising.

Salvaging each unique wreck is not a realistic option; in the first instance, due to the tremendous costs for conservation, excavation, storage, and exhibition. Consequently, *in situ* preservation has become more and more common and accepted as a long-term preservation method. It is also recommended as a first choice option by the

FIGURE 1 The warship Vasa displayed at the Vasa museum in Stockholm, Sweden. *© Lindman, Vasamuseum*

2001 UNESCO convention for the Protection of the Submerged Cultural Heritage which should be followed by all nations (UNESCO, 2001)

New information and observations have indicated that *Teredo navalis* is spreading into the southern parts of the Baltic Sea (Manders and Luth, 2004). The aggressive marine borers, with a worm-like appearance, are able to decompose wood constructions in a few years (Figure 2). This spread is possibly an effect of global climatic change and the worst case scenario would be a massive loss of unique archaeological shipwrecks and submerged wooden settlements or other wooden constructions in the Baltic.

The WreckProtect project started in May 2009 and ended in April 2011. The full title of the project was 'Strategies for the protection of shipwrecks in the Baltic Sea against forthcoming attack by wood degrading marine borers. A synthesis and

FIGURE 2 Heavy attack by *Teredo navalis*. The mollusc penetrates and digests the wood material forming up to 1 cm wide tunnels. *Photograph C. Björdal*

information project based on the effects of climatic changes'. It was financed mainly by the European Commission within the 7th framework programme, Theme Environment, and was a cross-disciplinary project involving scientists within geophysics, marine biology, marine archaeology, wood decay, and conservation. The consortia consisted of six partners from three countries, the Netherlands, Denmark, and Sweden, and was coordinated by SP technical research institute of Sweden. All work within the project was based on present knowledge and was carried out by careful literature studies in each field of interest. The accumulated knowledge was synthesized and evaluated and used in a cross-disciplinary context (Björdal and Gregory, in press; Gregory and Björdal, in press).

This paper will give the reader a short final report on the project and highlight the most important results.[1]

Summary description of the project objectives

The main scientific objectives were:

- To provide cultural resource managers, archaeologists, and conservators responsible for the long-term preservation of cultural heritage with tools for assessing and predicting the future spread of wood degrading organisms, especially *Teredo navalis*, which can rapidly attack underwater wooden objects and constructions.
- Recommend practical methods for protection of shipwrecks and historical settlements *in situ*, in order to prevent/delay their decay.
- To develop two user-friendly practical guidelines for prediction of risk zones and *in situ* protection of cultural heritage.

Project plan

The project was divided into five work packages, where the three scientific work packages are found in Table 1. The remaining two work packages (WP) were focused on management and dissemination of the project. This paper will give an overview of the scientific work only.

During the first year of the project, work was concentrated to WP 1 and WP 2.

WP 1: Coordinating present biological and environmental data

The aim was to synthesize environmental data from the Baltic Sea in order to produce a simple model that is able to predict the growth of the marine borer, *Teredo navalis*, in brackish waters.

TABLE 1

THE THREE SCIENTIFIC WORKPACKAGES OF WRECKPROTECT

Work packages (WP)	Title
WP 1	Coordinating present biological and environmental data
WP 2	Review of methods for protection of historical wreck and settlements in marine environments
WP 3	Strategy and tools for protection of cultural heritage

The environmental data sets used for this work included information from a relatively wide period of time; 1980–2008 for the hind cast data sets, and 2009–20 for the predicted data sets. The key environmental parameters that determine the species' distribution are salinity, temperature, oxygen, and ocean currents. Hydrographical datasets were obtained from the DHI company[2] and transferred into a GIS model. The spatial resolution of data for the model was 3and 9 nautical miles for the western and eastern Baltic respectively with average weekly measurements being obtained for both hind case and predicted data sets. The data were divided into two sets where one is the sea surface layer representing the larval habitat, and the other represents the adult habitat in the bottom layer. The Model Builder, one of the ESRI's ArcGIS extensions (www.esri.com), was used in this project. A step-by-step guide to model building is presented in the coming sections. Three models were built: one to merge the environmental data sets, a second to extract the spatial extent per year of particular merging scenarios, and the third to find the number of times a scenario will appear in a specific month over the investigated period of time (Frequency of Occurrence) of when situations are favourable for reproduction and growth of shipworm. To facilitate this, a full literature survey was conducted to elucidate the ecological criteria of *Teredo navalis* and point out which environmental parameters are important for survival and reproduction.

Although microbial decay was not included in the model, a comprehensive literature survey was conducted on these degraders to give a full picture of the biological degraders of wood in the marine environment.

Finally, a tool for the prediction of potential decay areas of *Teredo navalis* was synthesized. A very large amount of data was restructured and reformatted to a GIS (Geographical Information System) compatible format and a database was built for housing the data and restructuring them. The data was then loaded to the GIS program 'ArcGIS' for processing. Intense cross-disciplinary discussions were conducted and aimed specifically to categorize the environmental parameters into ecologically relevant classes. These classes were used in the GIS Geoprocessing program for delineating and predicting areas where forthcoming spread and attack of *Teredo navali*s are most likely to take place, that is, 'Hot Spots'. A verification of the model was based on known outbreaks of the *Teredo navalis* in the Baltic Sea region.

WP 2: Review of methods for protection of historical wreck and settlements in marine environments

An extensive literature review on methods for protection of shipwreck *in situ* was carried out. This included experimental studies and methods carried out and tested by conservators and marine archaeologists, as well as experiences from coastal engineering and the offshore industry when protecting wooden constructions such as piles or harbour constructions in marine environments. Additionally, a review of 'historical' literature, primarily from the Netherlands in the 1700s, was accomplished. The aims of all the literature reviews were to see what methods could be applicable to the *in situ* protection of shipwreck and other wooden archaeological artefacts.

As a result of the literature reviews, researchers from the aforementioned fields were invited to participate in a seminar to shed light on the results of the literature review and also highlight potential methods which had possibly not been covered in the literature review.

WP 3: Strategy and tools for protection of cultural heritage

In WP 3, two guidelines were produced. These were based on previous work carried out in WP 1 and WP 2 respectively, and aimed to be practical tools for stakeholder, managers and conservators working with protection of wooden underwater cultural heritage. It was the intention that both should be readily understandable and straightforward for use in practice. The first guideline was instructions on how to use the GIS model (produced in WP 1) as a tool for detection and prediction the spread of *Teredo navalis* in the Baltic Sea. It also included important background information on the Baltic Sea and *Teredo navalis*. The second guideline (based on WP 2) provided managers responsible for the protection of underwater cultural heritage with information and methods on how sites can be protected, the advantages and disadvantages of these protection measures, the threats, and cost benefit analyses.

Summary of main results achieved

WP 1: Coordinating present biological and environmental data

- A comprehensive study was presented on marine borers *Teredo navalis* (Figure 3a (Nair and Saraswarthy, 1971) and 3b), their ecology, biology, and their classification criteria with respect to the environmental parameters in their habitat. These parameters, summarized in Table 2, included salinity, temperature, dissolved oxygen, and current. Each parameter was studied and a numerical measure was established for its influence on the marine borer productivity and survivability both as adult and larvae.
- A full literature review for the historical documentation of shipworm attack and outbreaks, dating back from the present (2009) to the 1870s, in Danish territorial waters was carried out. Outbreaks of shipworm have occurred throughout the past 100 years or more in Danish territorial waters and the southern Baltic — it is not just a recent phenomenon. Recent reports from 1990 to 2009 state that these attacks appear to be worsening or are unprecedented. Outbreaks of *Teredo navalis* along the Baltic coast of Germany have been a reoccurring event since at least 1872, with records in almost each decade since then. Also in Danish waters large outbreaks have been seen in periods (1924–26, 1932–35, 1937–1941, 1947–50, 1955–60). In the 1970s and 1980s there was a dearth of literature relating to attacks, but in the 1990s problems seemed to start again.
- A full study on the microbial degraders was completed, giving an overview on the situation of microbial degradation by fungi and bacteria taking place in the Baltic Sea today. It was found that soft rot fungi and bacteria degrade the surface and interior layer of timbers in all types of saline, brackish, or fresh water environments (Björdal, in press). Where marine borers are absent, like in most part of the Baltic, these fungi and bacteria are the most important wood degraders in a long-term prospective, both above and beneath sediment.
- A model was built in ModelBuilder ArcGIS geoprocessing program for processing and combining the modelled environmental parameters. This model was used as a platform for additional models. The total spatial extent of a given

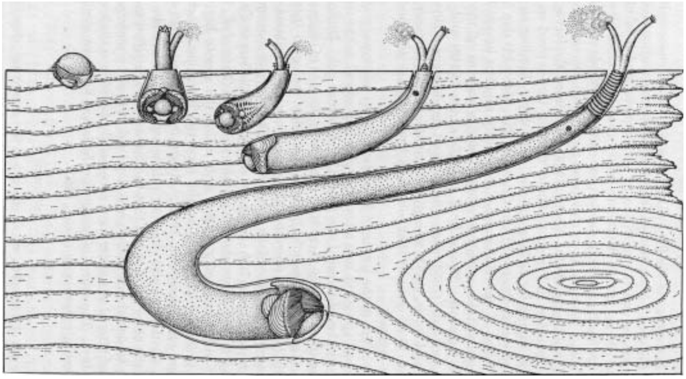

FIGURE 3 *Teredo navalis.*
FIGURE 3a Life-cycle of *T. navalis* (Nair and Saraswarthy, 1971).
FIGURE 3b Shell and muscular foot (ø 5mm) of an adult *T. Navalis*. *Photograph C. Appelqvist*

combination scenario over an entire year was calculated and presented in separate maps for each year. The model reconstructed the situation from 1980–2008, and subsequently predicted different scenarios for the future 2009–20. It was evident that the areas of risk zones fluctuated between years, but no significant extension of the geographical zone of spread could be observed (Figure 4a and b). However, the model showed a prolongation of the infestation season, as water temperatures during October will in future be warmer (Figure 5a and b). Thus, there will be a risk for an increased total number of larvae during a season, which gives a higher risk of growth and hence attack by *T. navalis*.

- The model was verified by information from known locations with and without attacks on test panels during the time periods of the model in the south western part of the Baltic Sea and from records in modern and historical archives
- To conclude, an increased number of larvae could be expected in the Baltic Sea, but not a spread into new areas.

Table 2

ENVIRONMENTAL PARAMETERS FOR THE SURVIVAL OF SHIPWORM LARVAE AND ADULTS

Larvae			
Class	*1*	*2*	*3*
Temperature (°C)	< 7 lethal	7–12 survival	> 12 development possible
Salinity (PSU)	< 5 lethal	5–8 survival	> 8 metamorphosis possible
Oxygen (mg O_2/l)	< 1 lethal 24 hr	1–4 effect on physiology	> 4 healthy condition
Currents (m/s)	< 0.1 (<120 km/2wks)	0.1–0.2 (120–240 km/2wks)	> 0.2 (>240 km/2 wks)
Adults			
Class	*1*	*2*	*3*
Temperature (°C)	< - 2 lethal	-2–11 survival	> 11 reproduction possible
Salinity (PSU)	< 4 lethal	4–8 survival	> 8 reproduction possible
Oxygen (mg O_2/l)	< 1 lethal 4 wks	1–4 effect on physiology	> 4 healthy condition

WP 2: Review of methods for protection of historical wreck and settlements in marine environments

- The literature review examined over 1000 articles, reports, and books. Summarily, many of the historical methods, although fascinating, were not applicable to *in situ* preservation of archaeological finds against shipworm. Likewise modern methods used by the wood industry are not applicable as they include simply using different materials to wood or impregnation with toxic chemicals unsuitable for marine archaeological purposes. The most successful and applicable methods appear to be physical barriers which either prevent the shipworm attacking the wood or making the environment unfavourable for their growth. These methods have included covering with plastic materials and geotextiles or creating an artificial burial mound over a wreck with sand bags or other means which utilize the natural transport of sediment within the water column around a site (Figure 6).

WP 3: Strategy and tools for protection of cultural heritage

Two guidelines were produced:

Guideline for prediction of decay by shipworm in the Baltic Sea[3]

A user-friendly guideline with information and instructions on how to predict the spread of *Teredo navalis* was written. A translation of data (scientific) was disseminated to the stakeholders such as policymakers, managers of cultural heritage, and a larger public. As the guidelines involve the use of a GIS-model, additional information directed to persons familiar with GIS modelling was provided. General information on the biological degraders in the Baltic Sea was given with a main focus on the growth and reproduction of *Teredo navalis*. With help of this tool and information, it is now possible to identify areas in the Baltic Sea where *Teredo navalis* could be active. When WreckProtect GIS Map is combined with national GIS maps with

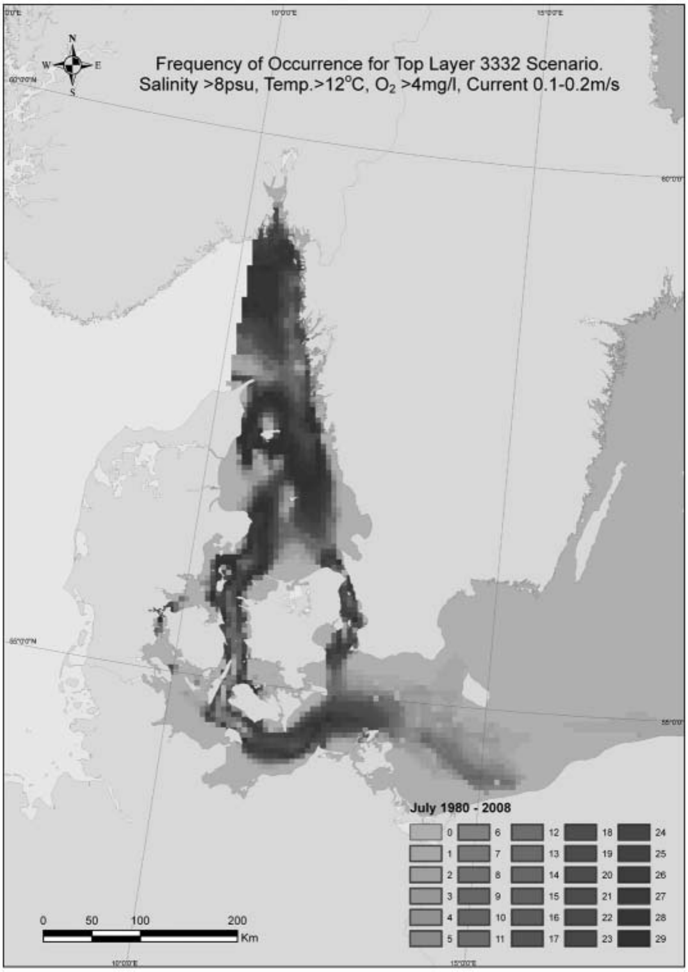

FIGURE 4 Spread of *Teredo navalis*. Top layer/larvae: No significant difference in spread into the Baltic Sea of *Teredo navalis* in the hind cast GIS map of July 1989–2009 (Figure 4a), compared to predicted spread July 2009–20 (Figure 4 b).

positions of historical wrecks, stakeholders in countries surrounding the Baltic Sea will be able to identify wrecks in risk zones and take the necessary precautions.

Guideline for the protection of wrecks including cost-benefit analysis[4]
Instructions on how to protect submerged wooden cultural heritage against deteriorating factors. This means not only the *Teredo navalis*, but also, for example, abrasion and human factors. The protection methods for in situ preservation are explained carefully with instructions, illustrating photos, tips, and suggested reading.

A cost-benefit analysis on *in situ* versus *ex situ* (excavation) is included and examples show very clearly that a full excavation, conservation, and exhibition of a larger shipwreck is very expensive and could be estimated roughly as 700 times as costly compared to *in situ* protection.

The guideline should be a tool for managers responsible for the protection of underwater cultural heritage to make decisions on whether sites can be protected,

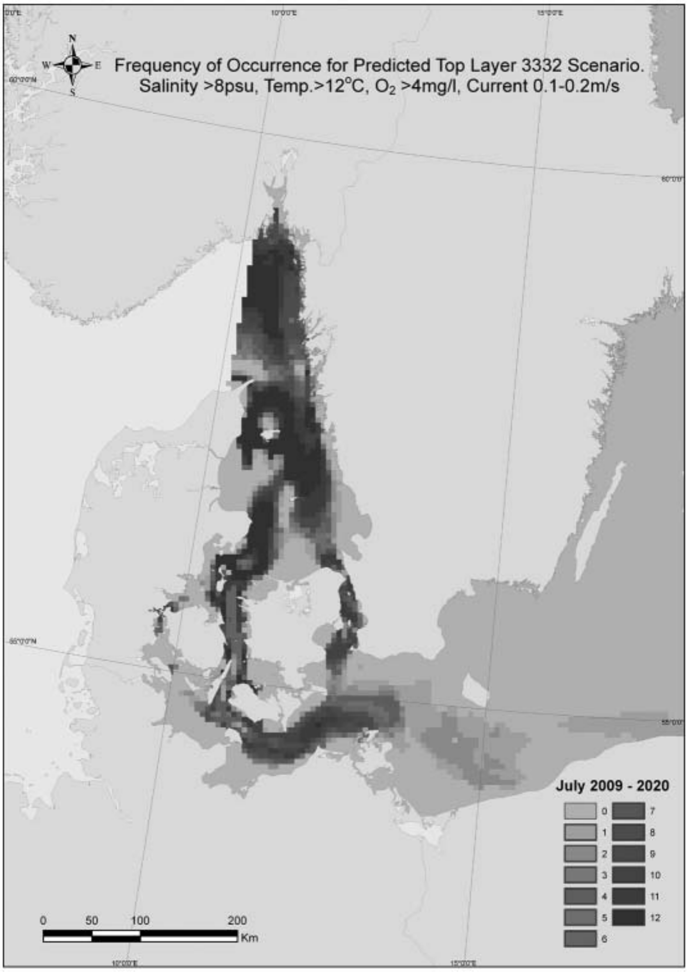

FIGURE 4b

how they can be protected, the advantages and disadvantages and the costs of these actions compared to *ex situ* conservation. The methods are applicable to hulls that are partly embedded in the sediments, which include wrecks in all waters such as the Mediterranean and the Baltic Sea.

Conclusion

The outcome of WreckProtect has provided stakeholders, managers, marine archaeologists, and conservators in Europe, that are responsible for long-term preservation of cultural heritage, with new tools for tracking environmental changes that endanger the long term preservation of historical shipwreck, as well as offer methods for *in situ* protection based on the most cost efficient choice. By using the guidelines, sites and unique historical shipwreck which are at threat from marine borers can be identified and prioritized for protection and saved for future generations.

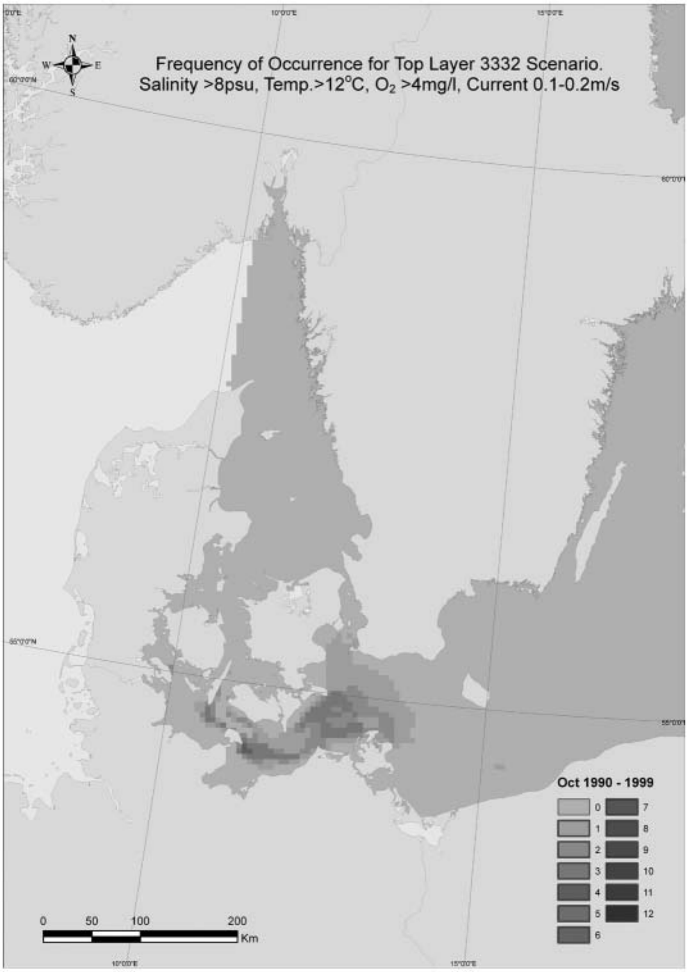

FIGURE 5 Occurrence of *Teredo navalis* in October. Top layer/ larvae. Frequency of occurrence in October 1990–99 (Figure 5a) is less frequent than the spread and frequency of occurrence of *Teredo navalis* found for the future period (Figure 5b). Frequency of occurrence of *Teredo navalis* in October month 2009–20 is based on future climate data, and shows a more frequent occurrence and wider spread in October, due to the warmer waters.

The awareness of shipwreck as vulnerable and important cultural heritage objects has been highlighted and the processes that endanger the long-term preservation have been enlightened. Scientific papers and conference proceedings, as well as a monograph dedicated to the topic, are important end products of the project that will be available for an international forum. WreckProtect has pointed out a need for further research within this multidisciplinary area and it is hoped that the project can inspire and encourage continued work dedicated to the long-term preservation of historical shipwreck *in situ*.

Acknowledgement

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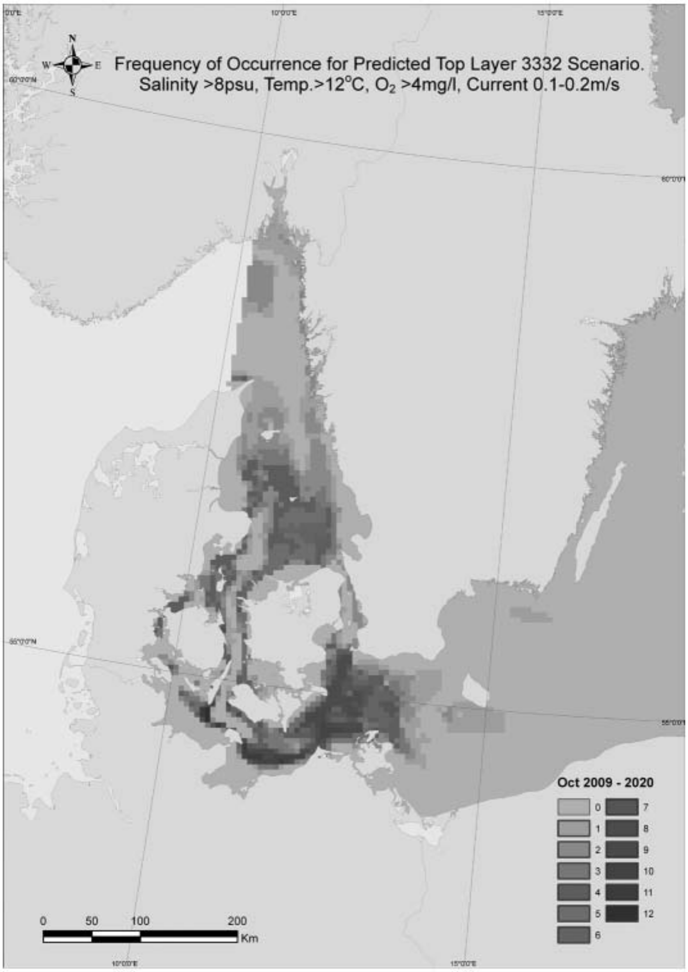

FIGURE 5b

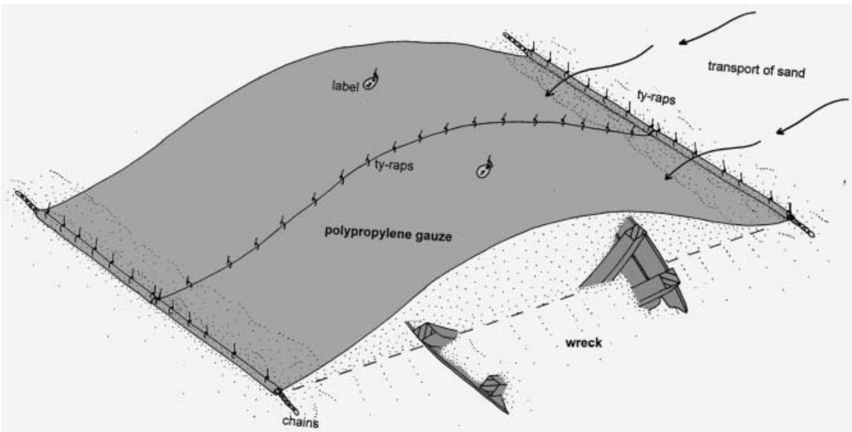

FIGURE 6 A method using sediment transport and a porous net to cover a wreck with sediment and preventing attack by shipworm.
Drawing by M. Manders, RCE

Notes

[1] For detailed information on results, we recommend the guidelines on <www.wreckprotect.eu> and the project monograph (Björdal and Gregory, 2012).

[2] <www.dhigroup.com>.

[3] The Guideline for prediction of decay is freely available as a PDF download from <www.wreckprotect.eu>. User-friendly maps can be downloaded for use in database/GIS systems from <www.wreckprotect.eu>. For those who do not have their own systems, MACHU GIS (Managing Cultural Heritage Underwater, a European Project under the Culture 2000 programme 2006–09) is available for (restricted) use at <www.machuproject.eu>.

[4] The guideline is available, including the cost benefit analysis, from <www.wreckprotect.eu>.

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Charlotte Gjelstrup Björdal gained a BSc in conservation from the Royal Academy of Arts, Copenhagen, 1986, specializing in conservation of waterlogged archaeological wood. In 2000 she defended her doctoral thesis 'Waterlogged Archaeological Wood — Biodegradation and its Implication for Conservation', at the Dept of Wood Science, Swedish University of Agricultural Sciences. During the last fifteen years her research has focused on microbial degradation processes of archaeological wood in marine and terrestrial environments; *in situ* preservation, decay processes, and reburial techniques for shipwrecks and other historical constructions are ongoing research topics. Currently she is the director of the Conservation Program at the Dept of Conservation, University of Gothenburg, Sweden.

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