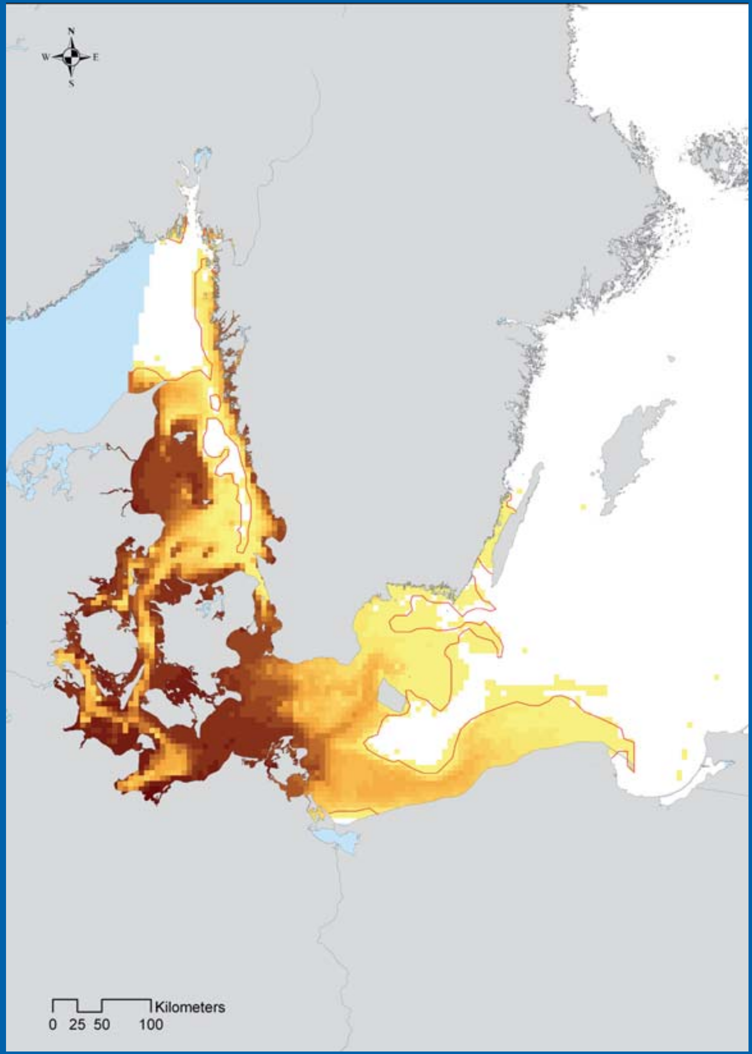


# Guidelines for predicting decay by shipworm in the Baltic Sea

2011

# Guidelines for predicting decay by shipworm in the Baltic Sea

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wreckProtect

# Content

# Introduction

This guideline will focus on both the spread of *Teredo navalis*, the only shipworm found in the Baltic today, and how to identify hot-spots which are those areas at risk of infestation by this marine borer. The basic requirements for *Teredo navalis* to grow, reproduce and recruit larvæ are summarized. Finally a review on historical outbreaks during the last century is presented.

The practical use of modelling tool ArcGIS developed by the EU-project Wreckprotect to identify areas that may encourage spread of the shipworm is described. Results from modelling the next 10 years (2010-2020) highlight regions in the Baltic Sea that may be vulnerable to shipworm attack. The model will be a helpful management tool because it indicates where action is needed to prevent loss of our maritime heritage.

# 1 About the guideline

This guideline aims at showing what to do when significant maritime cultural heritage within an area risks attack by wood degrading organisms. In this report we propose a strategy for such challenging situations:

1. Compile historical knowledge of outbreaks of attacks within the area.
2. Find out which species of shipworms have been identified in the area and study their requirements for survival, growth, reproduction and larval recruitment.
3. Investigate the current geographical distribution of these species to determine the risk of spread from any established populations, verify the model, and define the baseline for future studies.
4. Obtain hydrographical data for the relevant environmental parameters.
5. Use a model builder, such as ArcGIS, to illustrate the spatial and temporal distribution of environmental parameters.
6. Conduct monitoring on wrecks and/or historical remains.

As a case study, we can use the spread of shipworms in the Baltic Sea. The model organism is the shipworm *Teredo navalis*. The key environmental parameters that determine the species' distribution are salinity, temperature, oxygen, and ocean currents. Hydrographical datasets were obtained from the DHI company (www.dhigroup.com) and transferred into a GIS model. 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). Maps to show these scenarios are presented later in this report.
Details of how to access the model is given online on the Wreck Protect homepage (www.wreckprotect.eu).

# 2 The Baltic Sea

The Baltic Sea is almost an enclosed basin. Salt water inflow is restricted and this has resulted in stratification in the shallow parts and also to anoxic seawater conditions in the deeper parts of the Baltic proper. The brackish nature, low winter temperature, low oxygen content at the sea bottom and the prevailing ocean currents in the Baltic Sea have great impact on the vertical and horizontal distribution of marine wood boring organisms. This environment also slows bacterial decay and thereby preserves archaeologically important shipwrecks for many centuries. This provides us with an outstanding historical archive worthy of UNESCO protection. Recent investigation of the Baltic Sea reveals new outbreaks of *Teredo navalis*, which have infested many shipwrecks in the southern part of the Baltic as well as in the Kattegat.

This shipworm is highly productive and can destroy shipwrecks in a relatively short time if the surrounding environmental parameters are favourable for their survival and reproduction. The *in situ* preservation of these archaeologically significant finds is the most viable option to ensure their survival for generations to come (see also WreckProtect's Guidelines for the protection of submerged archaeological sites *in situ*). The effectiveness of *in situ* preservation requires thorough investigation and spatial information about the environmental parameters for the Baltic Sea regions that are most at risk of shipworm attack. This guideline tackles this issue and describes the hot spot areas as a GIS layer that can be used for preservation planning and archaeological resource management. In this work the Baltic Sea marine area is as described by the HELCOM definition (http://www.helcom.fi/GIS/en_GB/HelcomGIS/) and includes the Skagerrak as it is the gateway to the Kattegat.

**Geological history of the Baltic**

The Baltic Sea and Kattegat region is very young both from a geological perspective and as a marine ecosystem. The Baltic Sea has, since the last glaciation, been affected by variable freshwater and brackish periods. The meltwater from the Fennoscandian ice sheet formed the Baltic Ice Lake approximately 15000 years ago in the area where the brackish Baltic Sea is situated today. It persisted until around 11590 cal. BP (Sauramo 1958) when a connection to the North Sea was

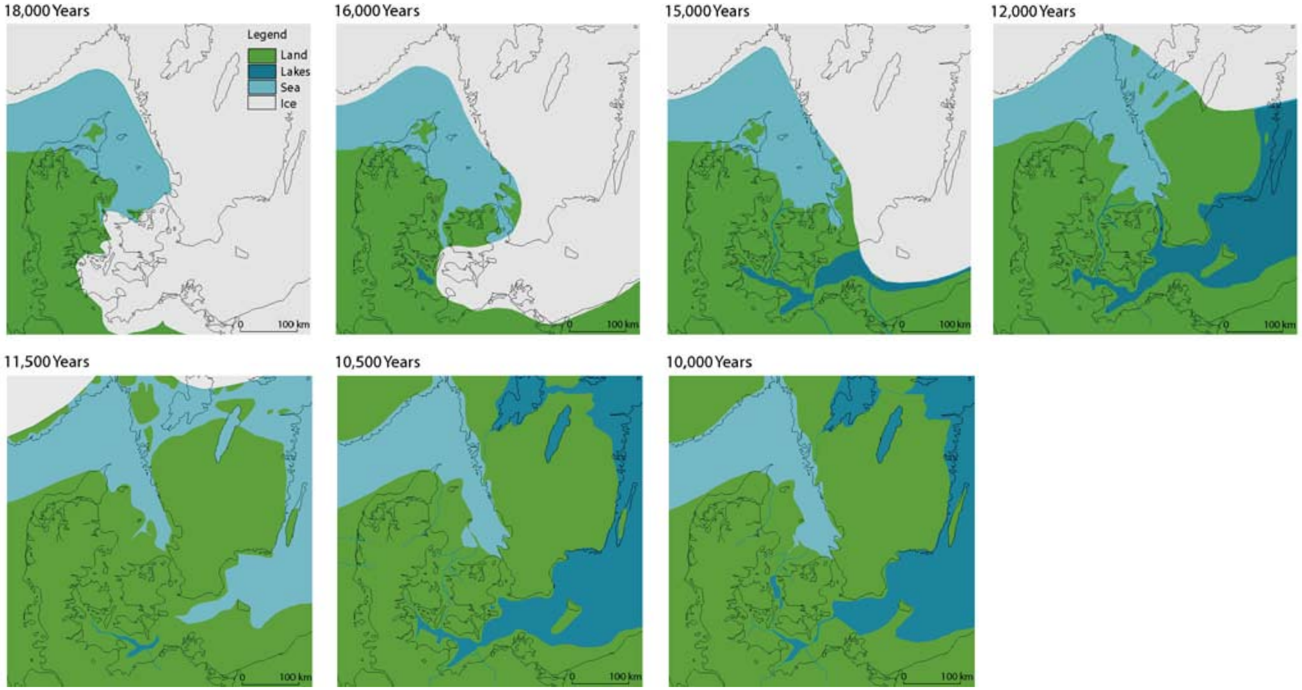



*Figure 1: Glacial and postglacial maps of the Baltic Sea showing the formation of Yolidia sea around 11500 years ago and the Ancylus Lake 10500 years ago (Jensen et al. 2002)*

established through south-central Sweden by the retreating ice margin. This caused a sudden drop of the dammed lake level by 25 m, and the introduction of more saline water into the Baltic Sea Basin (Björck 1995), thus marking the beginning of the first brackish period (Andersen and Borns Jr. 1997). With the formation of the Yoldia Sea, brackish conditions lasted just a few hundred years, and were succeeded by some 500 years of freshwater conditions (Svensson 1991). The rapid glacio-isostatic uplift closed the connection to the North Sea in south-central Sweden, and the Baltic Sea Basin became isolated from the world ocean at around 10,700 cal. BP (Svensson 1991, Björck 1995). This was the onset of the fresh water Ancylus Lake that was connected to the North Sea by a river, which today is located at the bottom of the Danish Straits.

Further meltwater from the world's ice sheets caused a rise in the sea level and periodic salt-water intrusions from the North Sea into the Baltic Sea Basin through the Danish Straits. These saline water inflows were first restricted to the southwestern Baltic Sea Basin. As the world ocean levels continued to rise, the result was the end of the Ancylus Lake and the onset of the brackish Littorina Sea approximately 8000 - 7500 years ago (Winterhalter et al. 1981, Björck 1995) allowing marine species to populate the area. The Littorina Sea had a higher average temperature than surrounding waters and as a result the salinity attained 8psu in the Bothnian Bay. During the mid-Holocene, around 5000 - 2500 years ago, a general cooling of the region began with a corresponding decrease in salinity. This marked the end of the Littorina Sea and the beginning of

| Table 1: Physical characteristic of the Skagerrak, Kattegat and the Baltic Sea (modified from Andersen & Pawlak 2006, Wennberg et al. 2006). | | | | | |
|---|---|---|---|---|---|
| Sub-area | Area | Volume | Salinity range | Max. depth | Average depth |
| | $km^2$ | $Km^3$ | Psu | M | M |
| 1. Baltic Proper | 211 069 | 13 045 | 5-10 | 459 | 62.1 |
| 2. Gulf of Bothnia | 115 516 | 6 389 | 0-7 | 230 | 60.2 |
| 3. Gulf of Finland | 29 600 | 1 100 | 0-7 | 123 | 38.0 |
| 4. Gulf of Riga | 16 330 | 424 | 6-10 | > 60 | 26.0 |
| 5. Danish Straits & Kattegat | 42 408 | 802 | 8-32 | 109 | 18.9 |
| Total Baltic Sea | 415 266 | 21 721 | 0-32 | 459 | 52.3 |
| Total Baltic Sea ecoregion | 409 828[2] | -------- | ---------- | ------- | ---------- |
| Total Skagerrak | ---------- | -------- | 33 | 725 | ---------- |

the Late Littorina Sea (at around 3000 cal BP) and later the formation of the Baltic Sea (Russel 1985) and its marine landscapes as we know them today (fig. 7).
Today the Kattegat, the Danish Straits and the Baltic Sea together comprise the second largest brackish area, after the Black Sea, in the world (Segerstråle 1957) with a number of basins varying from almost freshwater in the northern part of the Bothnian Bay to the saline waters of Kattegat with a distinct salinity gradient in the Danish Straits (table 1). The total volume of the Baltic Sea including the Danish Straits is approximately 21.700 $km^3$ with a surface area of 415.200 $km^2$ reaching depths of up to 459 m with an average depth of 52 m (Andersen & Pawlak 2006). Approximately 475 $km^3$ of freshwater passes through the Danish Straits annually. The Baltic Sea is also characterised by the almost total lack of tide (Hällfors et al. 1983), which makes the salinity regime very stable in very large areas. Many areas are temporally or permanently stratified, which together with the intense eutrophication causes large volumes to be depleted of oxygen (Ærtebjerg et al. 2003).

The permanent stratification is maintained by temperature differences in the water column, the large annual input of fresh water from the many rivers in the region and the occasional influx of higher density, more saline water from the Skagerrak over the thresholds in the Danish Straits. The weaker temporal stratification occurring in shallow waters will normally collapse due to storms during autumn and winter which agitate the water column. The Baltic Sea is also characterized by large annual changes in surface temperature with up to 4 months of ice coverage in the Bothnian Bay (Jansson 1980). The shallow Kattegat and the Danish Straits form the transition zone between the low saline Baltic water and high saline waters of the North Sea and the Atlantic Sea. Large islands, reefs and sandbanks dominate this area with remnants of river channels forming the deepest part. Numerous large inlets, bays and fiords are located along the coastline (fig. 2). The western Kattegat shores are characterised by a mixed geological composition of mainly sand, gravel and boulders, while bedrock dominates the eastern shores.

The transition from the Kattegat to the Baltic Sea is dominated by the sills at Gedser-Dars and in the Sound, which act as a physical barrier to the Baltic Sea for the relatively heavy saline waters of Kattegat. The Baltic Sea is split into a number of deep basins reaching depths of 459 m. The southern coast of the Baltic Sea is mainly characterised as exposed sandy shore often with lagoons separated from the sea by gravel and sand banks. Further north, in the Gulf of Finland and the Archipelago Sea, numerous skerries and islands span the Baltic Sea almost bridging the area between Åbo in Finland and the Stockholm Archipelago. Furthest north the shore is mostly

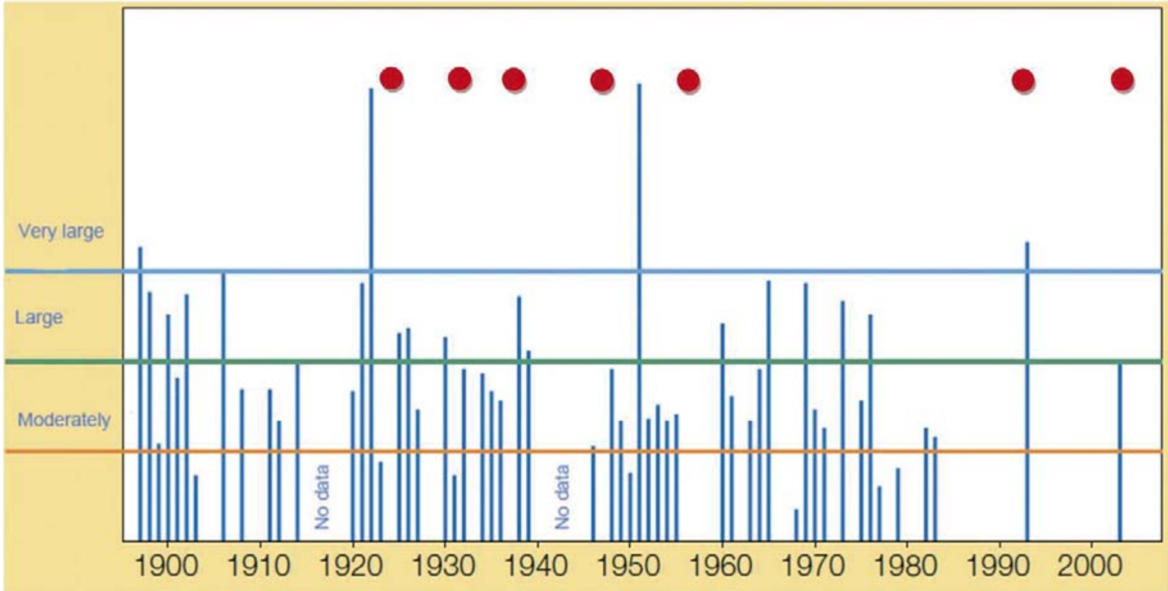



*Figure 2: Major Baltic Inflows from 1880, modified after Schinke and Matthäus (1989) and Meier and Gustafsson (2009). The red dots show the times when the shipworm attack has been seen, according to the aforementioned literature.*

composed of bedrock interspersed with many small gravely bays and lagoons. Furthermore, large areas are influenced by massive land rise with the seabed rising more than 8 mm per year in the Quarken area. This creates a unique range of habitats where the sea slowly develops into land.

**Historical attacks and risk of spreading**

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. Many publications consider the reasons for the spread of *Teredo navalis* and several hypotheses for the causes of this spreading have been proposed (Møhlenberg 2002):

- Invasive species spread in ship's ballast water
- The marine / water environment in and around the Baltic is less polluted
- Poorer quality wood used in marine constructions which is more vulnerable to attack
- Periodic influx of high salinity water into the Baltic. This is related to the meteorological phenomenon called the North Atlantic Oscillation
- Higher than average summer temperatures in the waters of the Baltic.

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. In 1938 Becker claims the eastern limit of attacks to be at Zingst (review in

Clapp and Kenk 1963). Also in Danish waters large outbreaks have been seen in periods (1924-1926, 1932-1935, 1937-1941, 1947-1950, 1955-1960). In the 1970s and 1980s there was a dearth of literature relating to attacks, but in the 1990s problems seemed to start again. Extensive infestations occurred 1993-1996 along the coast of Mecklenburg-Western Pomerania, as far east as Hiddensee (Sordyl et al 1998). It was also reported that in 1997 the shipworm spread around Sleswig in southern Germany and in southern Jutland.
Apart from reports of the spread and attack of shipworm, there appear to be various reasons for the spread and the two factors which stand out are higher than average summer water temperatures and periodic influx of high saline water from the Kattegat. Kristensen (1969) carried out a thorough study looking at shipworm attack between 1900 and 1967, attempting to correlate it with surface temperature and salinity. Kristensen concluded that only high summer temperatures and attacks correlate and that there are many reasons to be cautious when interpreting the data due to the many other parameters which could have influence.
Møhlenberg (2002) showed that in years when attacks were reported, average temperatures were higher than 17ºC as opposed to 15.7ºC in years without attack. Møhlenberg also introduces the idea that apart from higher than average summer temperatures there is a correlation between winter storms and western winds. These occur as a result of a large air pressure difference between Iceland and the Azores – the so called North Atlantic Oscillation index (NAO). This phenomenon can lead to inflows of highly saline and oxygenated water from the North Sea. These events are termed major Baltic inflows (MBI) – they are of episodic character and are the only mechanisms by which the central Baltic deep water is renewed. Although the cycle of water renewal has been well documented, the meteorological and oceanographic processes controlling this are still not totally understood (Schinke and Matthäus, 1998). Nevertheless it does appear that these inflows are characterised by two phases. The first is high pressure over the Baltic region with easterly winds, followed by several weeks of strong zonal wind and pressure fields over the North Atlantic and Europe. Several large inflows have been documented in the past as shown in figure 2.

The decreasing frequency and intensity of major inflows since the mid 1970s and their complete absence from 1983 to 1993 is explained by Schinke and Matthäus (1998) as being due to increased zonal circulation linked with intensified precipitation in the Baltic region and increased river run off to the Baltic during this period. It is interesting to note that some of the outbreaks of shipworm, as recorded from the documentary evidence, do coincide with these large incursions and may warrant further investigation – certainly for the periods from 1980 to the present where modelled data has been prepared and is presented in this guideline.

# 3 The study organism

**The biology and life history of *Teredo navalis***

Shipworms are highly specialized molluscs that drill into wood. There are about 65 species of true shipworms (Teredinidae) worldwide, and six of those reproduce in northern Europe (Turner 1966). The one causing most economic problems is the cosmopolite *Teredo navalis*, which is the only species found active today in the south-eastern part of the Baltic Sea. Infestation of wood by shipworms occurs during the larval phase of their lifecycle (fig. 3). The larvae of *T. navalis* are planktotrophic, meaning they have to feed on plankton during the free-swimming larval phase (fig. 4). After about 14 days in the water column, at a size of approximately 0.25mm, they are mature enough to settle onto wood. If no suitable substrate is available they can survive for an additional two weeks (Scheltema 1971). After successful settlement they pass through the critical metamorphosis stage. The larva then changes from a juvenile to an adult that will never naturally leave the piece of wood. Repeated rasping movements by the fine serrated shells (fig. 5) make a perfectly circular subway within the wood. With help from unique endosymbiotic bacteria (*Teredinibacter turnerae*), which produce cellulolytic enzymes, *T. navalis* eats its way into wood (Distel et al. 2002). The small helmet-like shells cover only the anterior part of the adult animal and a thin calcareous layer protects the rest of the elongated body. At the posterior end, a pair of retractable

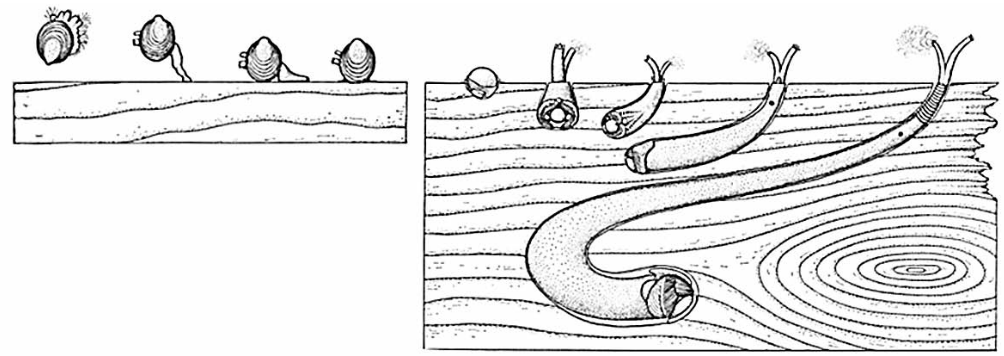


*Figure 3: Life-cycle of* T. navalis *from Nair and Saraswarthy 1971*

*Figure 4: Four day old larvae of T. navalis (74 x 80 µ). Photo C. Appelqvist.*

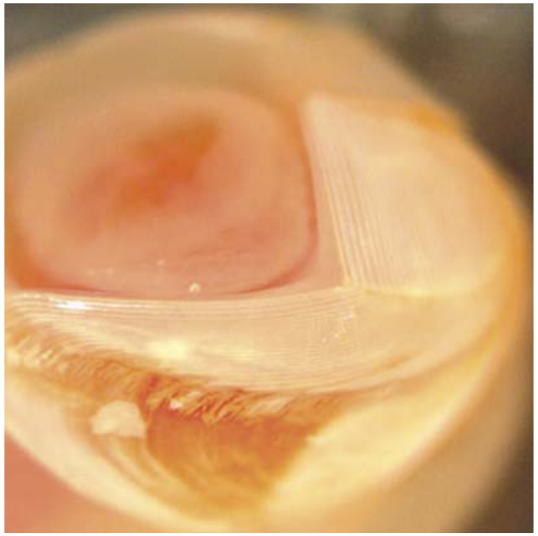


*Figure 5: Shell and muscular foot (ø 5mm) of an adult T. Navalis. Photo C. Appelqvist.*

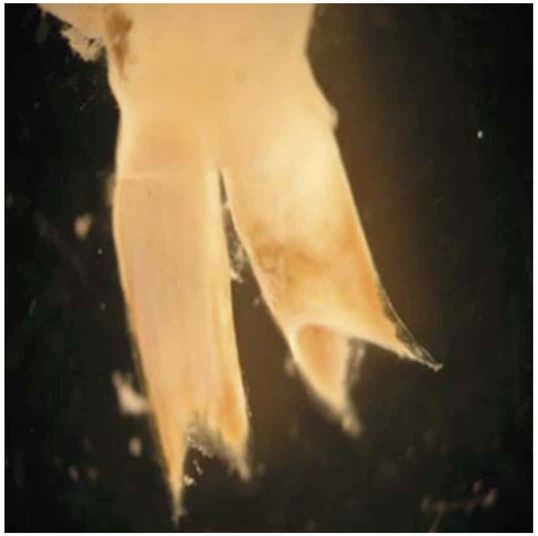


*Figure 6: A pair of pallets from T. navalis (5x2mm). Photo C. Appelqvist.*

*Figure 7: Siphons extended from a piece of wood. Photo C. Appelqvist.*

siphons, and the two species- specific pallets are situated (fig. 6). By sealing their burrow with the pallets they can avoid unfavourable conditions from the surrounding water, and survive for at least three weeks upon stored glycogen (Lane 1959). The tube-like siphons (fig. 7), the only part of the animal that is visible outside the wood, are used for filtration of plankton and obtaining an oxygen supply. By filter feeding they receive nutritional lipids and proteins (Mann and Gallager 1985). However, they can survive and reproduce without plankton feeding for at least two years because the cellulolytic nitrogen-fixing symbionts also provide an internal source of nitrogen to supplement the host's protein-deficient diet (Ahuja et al. 2004, Waterbury et al. 1983). As the adults grow they follow the grain of the wood, avoid knots or joints and seldom interfere with others or break into the burrow of their neighbours. At temperatures of 20˚C, *T. navalis* becomes sexually mature at three weeks old (Culliney 1975). After fertilization the larvae develop in a brood pouch for two weeks before they are dispersed. Depending on age, population density, wood type and the environment the adult size of *T. navalis* range from a few millimetres to one meter.

### The ecology of *Teredo navalis*

Several environmental factors in seawater affect the physiological and ecological behaviour of shipworms. However, the key physical parameters are salinity, temperature, dissolved oxygen, ocean currents and the availability of wooden substrate. The occurrence, abundance and intensity of shipworm attacks are dependent on these factors, which usually vary widely from year to year. These climate fluctuations contribute to the periodically reoccurring devastations often separated by long periods of no attacks in an area. The distribution pattern of a shipworm species correlated to environmental key factors may also vary between geographically distinguished localities due to genetic variation and local adaptations. For example, the worldwide-distributed species *T. navalis* shows a wide range of tolerance for different environmental parameters.

*Salinity*

As early as 1733 Sellius believed that salinity was limiting the distribution of teredinids. Later, White 1929, Scheltema and Truitt 1954, Culliney 1970, among others supported this hypothesis. However, in 1979 Rayner showed that adults of estuarine shipworm species survived and developed larvae in aquaria at salinity conditions outside the salinity range in the field. This is also confirmed by experiments on larvae (Hoagland 1986). She showed wider salinity tolerance in the lab than in the ocean for both *Teredo bartschi* and *Teredo navalis*. Junguera and co-workers (1989) also suggest that salinity is not the determining factor for the distribution of teredinids in Brazil. The responses to salinity in the cosmopolitan species *T. navalis* show a remarkable similarity throughout different parts of the world (Blum 1922, Roch 1932, Imai et al. 1950, Culliney 1970, Kühl 1972, Hoagland 1983, Spicer and Stromberg 2003), although local adaptations might have evolved in such a way that preferably each population should be studied individually, especially in estuarine regions. Normal boring activities by adults generally occur in salinities down to 7-9 PSU and salinity less than 4-6 PSU is lethal to them. With the exception of the Black Sea where 8 PSU is lethal (Soldatova 1960). Reproduction is possible in salinities above 8-9 PSU (Sordyl et al 1998, HELCOM data base). There is a presumption that bivalve larvae are less tolerant than adults to extremes in salinity, a hypothesis supported in the literature by Scheltema and Truitt (1954). However, Hoagland (1986) found that although the upper salinity tolerance of larvae of *T. navalis* was far less than of adults, the lower limit was similar. The adults remain active between 7-45 PSU and the larvae were active at 6-31 PSU. In her study the lethal limit was fixed to 5 PSU for larvae of *T. navalis*. The age of bivalve larvae is crucial in their resistance to salinity variations (Loosanoff and Davis 1963)although more experimental work is needed on this subject. The tolerance levels are summarized in table 2.

*Temperature*

Temperature is an important factor influencing not only the biological systems but also the hydrographical conditions, for example the precipitation of salt, thereby affecting salinity. For shipworms it is a limiting factor for reproduction, growth and geographical distribution. One suggestion for the geographical extension of *T. navalis* to the southern Baltic has been that the species is more tolerant to lower salt concentions because of the warming of the Baltic. However, this hypothesis has not been tested. For many invertebrates and vertebrates, an increased environmental temperature results in an accelerated energy metabolism but also increased basal metabolic rate. This may in turn lead to less energy available for osmoregulation and thus make them less tolerant to extreme salinities (Einarson 1993).

*T. navalis* is found all over the world and the species can withstand a wide range of temperatures. In cold waters, found for example in Sweden, adults can tolerate temperatures from -1.4˚C to 30˚C and are most active between 15-25˚C (Roch 1932). This corresponds well with the results from the Black Sea where optimal temperatures are between 15-25˚C and -1˚C is lethal (Zvorykin 1941). In the Elbe estuary, Germany, active boring occurs at temperatures between 5-27˚C (Runnström 1925). For shipworms in temperate oceans, spawning activity is stimulated by rising temperatures in spring. In the Atlantic, *T. navalis* have a long spawning season starting in early summer lasting to late fall. Along the north-eastern coast of the US the species spawns at temperatures above 11-15˚C (Grave 1928, Nelson 1928, Loosanoff and Davis 1963, Culliney 1975). In both Runnström's 1925 study in the Elbe estuary and Roch's investigation in 1940 of the Adriatic Sea, spawning occurred between 11-24˚C. Larvae are more sensitive to lower temperatures than adults. In 1986 Hoagland observed active larvae at 10-29˚C. Experiments by Kudinova-Pasternak (1962) showed optimum activity at 18-27˚C, and temperatures below 10˚C or above 30˚C were lethal. Larvae of *T. navalis* from Canadian waters needed a minimum temperature for survival at 7.5 ˚C (M´Gonigle 1926). The conclusions from this literature review are that adults of *T. navalis* are tolerant to temperatures from -1.4 to 30 ˚C and start spawning at 11˚C. The larvae are active between 7.5-30˚C, and metamorphosis is possible at temperatures above 12˚C. See table 1.

*Oxygen*

Many well-preserved wrecks in the Baltic Sea are situated in oxygen-depleted areas. In these environments the deterioration process for both microorganisms and invertebrates is absent or very slow. Oxygen is an important parameter to be considered in relation to attacks by shipworms, yet there is a lack of experiments on their requirements for dissolved oxygen. The data available today principally concerns oxygen consumption in different stress situations (Spicer and Stromberg 2003, Mann and Gallager 1984, Soldatova 1960, Lane and Tierney 1951). Surprisingly, in one study from 1932, Roch observed adults of *T. navalis* to remain active when the oxygen level fell to 0.98 mg $O_2$/L. For the modelling work described here the classification criteria for the oxygen tolerance is mainly based on investigations on other bivalves (Baker and Mann 1992, Miller et al 2002, Long et al 2008). The minimum tolerance levels are estimated to less than 1mg $O_2$/L is lethal in 24 hours for larvae and after 1 month for adults.

| **Parameter** | **a) Adults** | **b) Larvae** |
|---|---|---|
| Temperature (˚C) | > 11 | > 12 |
| Salinity (PSU) | > 8 | > 8 |
| Oxygen (mg O2/l) | > 4 | > 4 |

*Table 2: critical environmental parameters of* T. navalis *living in temperate waters. a) Reproduction possible by adults, b) possible metamorphosis of larvae = risk of new attacks.*

*Currents*

Ocean currents are the most important natural vector for dispersal of adult shipworms within drift-wood and spread of planktonic offspring to new habitats. The free-swimming larval stage of *T. navalis* persists for 2 – 4 weeks. The first 14 days are necessary to develop into settling maturity, but if no wood substrate is available at that time they can survive for at least additional 2 weeks. This larviparous life history trait makes it possible for *T. navalis* to spread over long distances. For accurate estimation and determination of the chance of spread both the velocity and the direction of the current are desirable.

**The effect of *Teredo* attack on shipwrecks**

Shipworms perform a vital ecosystem service by degrading terrestrial material in the sea, but this also causes extensive damage to economically and culturally important marine wooden structures. Unlike other marine biofouling, damage caused by shipworms is an irreversible process. The consumed wood is gone forever. Ongoing degradation can be stopped for example by moving a vessel into fresh water (fresh water has a salinity below 4 PSU), draining a ship hull for at least one month, or covering a wreck with *in situ* protection methods. The infestation of wood takes place while the shipworm is in its mobile stage, a larvae. If a piece of wood is submerged or a wooden wreck is exposed during the larval season, new attacks can occur within 24 hours. The occurrence and extent of attacks are among other factors dependant on larval supply, competition with other fouling organisms, the success of metamorphosis and types of wood. The growth rate of shipworms varies a lot between species and geographical location. It is also directly related to the prevailing hydrographical conditions of the surrounding water. However, a supplement of nutritional rich food in form of phytoplankton seems to have no effect on the growth rate, at least when they have sufficient wood to feed on (Mann and Gallager 1985b). Instead growth is highly dependent on the number of individuals that have settled in the same piece of wood and compete for space (Norman 1977). The rate of growth varies also with age and place in the reproductive cycle. Studies in the western Atlantic on *T. navalis* show maximum lengths of 32 mm the first month, and up to 400 mm in one year at 20-23 ˚C (Mann and Gallager 1985a). In Scandinavian waters the highest growth rate occurs at temperatures over 15˚C and the longest specimen found after 18 months measured 270 mm, and 590 mm after 36 months (Norman 1977, Kristensen 1979). Growth stopped at temperatures below 5 ˚C. Adult shipworms have few predators and the life span of *T. navalis* can be at least 3 years (Kristensen 1979). With a growth rate of 0.5 – 1 mm per day in temperate waters like Scandinavia a 20 cm long piece of wood would be completely consumed by *T. navalis* within a year (Picture X).

*Figure 8: X-ray photo shows the calcified shells and lined tube walls of shipworm attacks in an untreated fir panel (200x75 mm) that has been submerged for three months in summer at the Swedish west coast. The large tube walls are due to the species Psiloteredo megotara while the others are by Teredo navalis.*

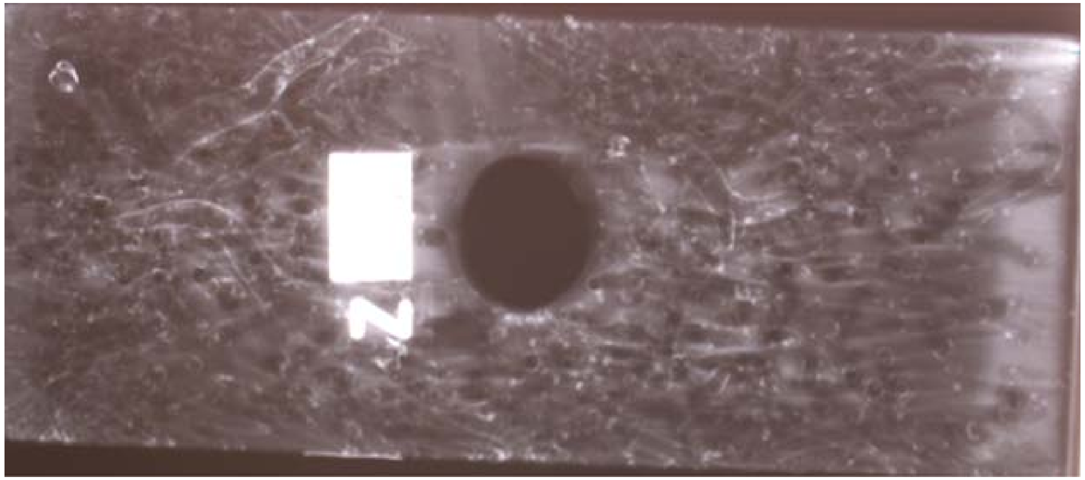


*Figure 9: The fishing vessel Rio heavily infested by shipworms and other marine organisms after six years on the seabed. Photo credit: Staffan von Arbin/Bohusläns Museum*

An ongoing study on the degradation rate of a wooden wreck is taking place at the Swedish west coast. In 2003, a 15 metre long fishing vessel built of oak was submerged at a water depth of 16 meters. After a few years the hull was totally infested by shipworms and after 6 years completely destroyed. The main part of the hull is still standing upright on the sea bed but is starting to fall apart. Many of the shipworms are dead but the calcified tubes from old boreholes and the relatively connected surface layer of the wood are still holding the structure together (fig. 9).

At a Danish site, the Kolding Cog, the same process was observed. The shipworm had weakened the structural timbers to such an extent that the upper parts had disintegrated and were lost. It was only the lower parts of the wreck, buried in sediment that had survived.

Figure 10 shows the locations of known wooden wrecks in Danish waters but there is limited information on their state of preservation and if they have been attacked or threatened by shipworm. Hence the need for this Guideline.

**What happens if *Teredo* spreads?**

If *Teredo navalis* spreads further into the Baltic Sea, highly valuable historical remains may be lost within a few years or decades. All wood at the seabed or floating timbers in waters with temperatures above 12 ˚C, salinity higher than 8 PSU, and high oxygen concentrations might be infested. The natural

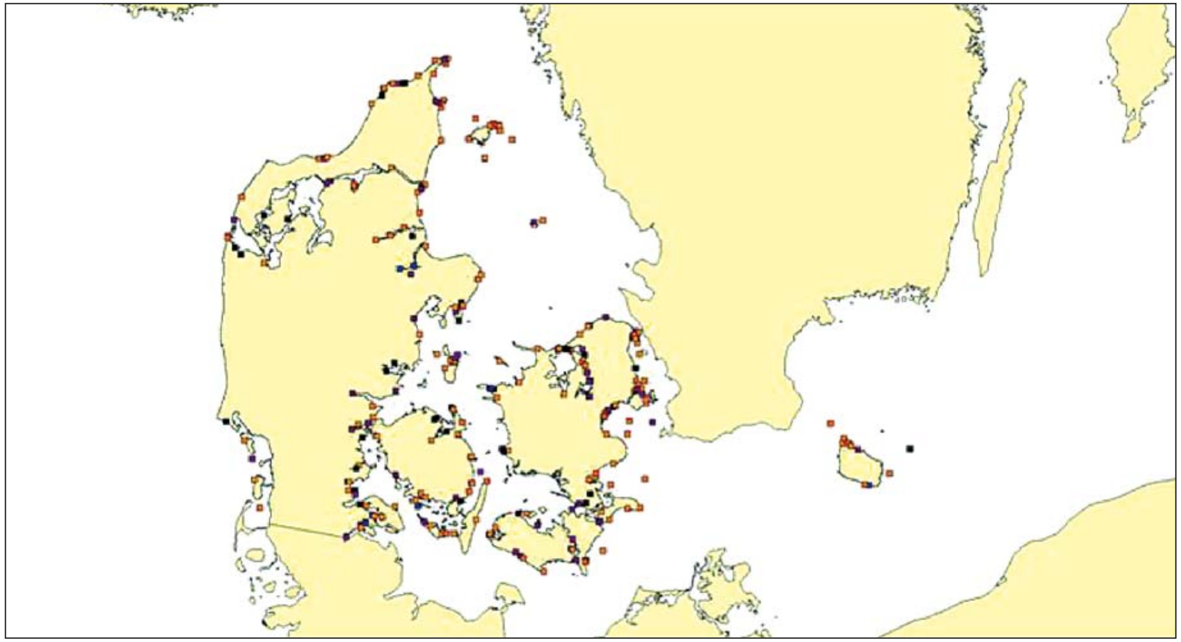


*Figure 10: Known locations of wooden shipwrecks in Danish Waters. Picture The Viking Ship Museum, Roskilde.*

spreading of shipworms occurs in adults within drift wood or in larvae by ocean currents. However, human activities help nature along the way. Species can be transferred to new areas as adults within wooden ship hulls and fishing gear, and as larvae by ballast water. Sometimes, when scientists move organisms for research purposes, they might unintentionally spread non-native species. A terror scenario for the marine archaeology treasures in the Baltic Sea would be human mediated transfer of a brackish water shipworm species. For example, member of the genus Nausitora and Neoteredo inhabit estuaries and rivers around the world. However, the environmental conditions must be suitable for survival, larval settlement, growth, and reproduction before a species can become an established member of the local fauna.

*Teredo navalis* eats its way through pieces of wood. This reduces strength and wood may collapse or crumbe either underwater during retrieval or conservation/drying. The wood itself becomes more vulnerable to abrasion and other mechanical deterioration. But especially for the well preserved shipwreck – for which the Baltic Sea is famous – the *Teredo navalis* poses a threat. Shipworm attack can cause shipwreck to lose their structural strength and collapse under their own weight in a short period of time, maybe even months.

# 4 The Model

Modelling in a GIS allows scientists to visually inspect the different parameters they are dealing with and allow questions such as how do the parameters interact, how good is the hypothesis of combining or algebraically processing these parameters.
Prior to starting the hard work of model building, the output of the modelling process has to be established. It is important to decide the outcome of the modelling in order to determine the accuracy of your results. Having done that one needs to identify the layers containing the attributes and the information required for the model. The following flow chart (fig. 11) gives a simple overview of model building.

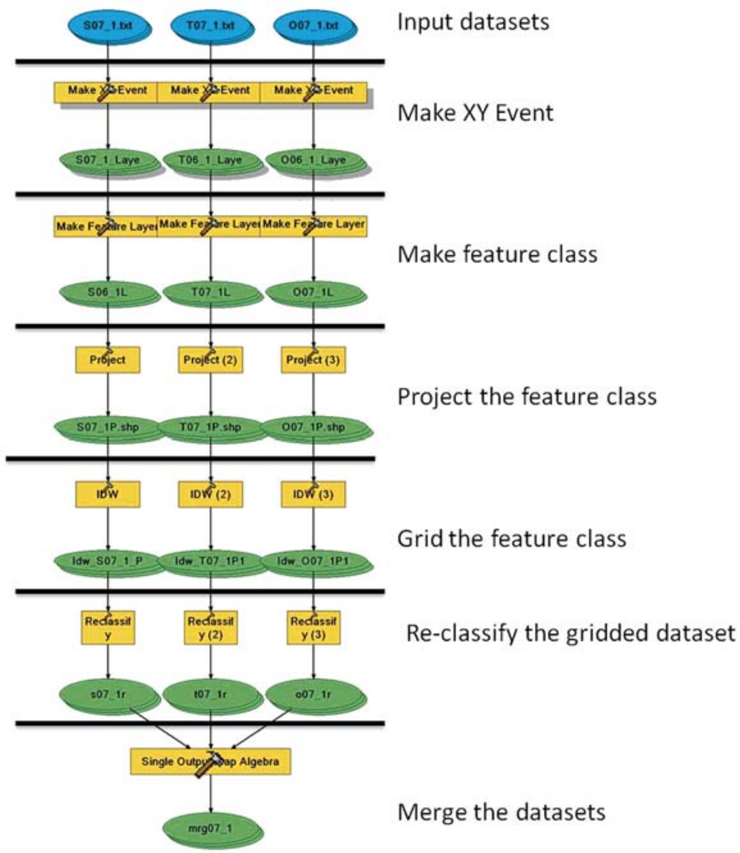



*Figure 11: flow chart for the model building process.*

| **Top layer, classification for *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 O2/l) | < 1 lethal 24 hr | 1 – 4 effect on physiology | > 4 healthy condition |
| Currents (m/s) | 0.1 (<120km/2wks) | 0.1-0.2 (120-240 km/2wks) | > 0.2 (>240 km/2wks) |
| **Bottom layer, classification for *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 O2/l) | < 1 lethal 4 wks | 1 - 4 effect on physiology | > 4 healthy condition |

*Table 3: The classification criteria for various environmental parameters.*

Modelling is a very attractive tool when science must be integrated with policy, also when multidisciplinary scientists are working together, and when spatial representation issues are important.

**Classification criteria for environmental parameters**
The tolerance levels for the environmental parameters of salinity, temperature, and oxygen are divided into three classes following the degree of influence on the physiology of the shipworm *T. navalis* (based on the literature review described above). Class 1 are lethal limits, class 2 state of stress, and class 3 are possible levels for development and metamorphosis of larvae and reproduction of adults. The classes for currents are set to three ecological relevant levels, see table 3. Due to the variation in type and results obtained from various experiments it is difficult to draw a sharp line at a certain value (e.g. for the lethal limit). Bear in mind that the tolerance limits are also dependent on the age, the condition of the animal and the time of exposure to extreme environments. For example, an adult shipworm can tolerate a salinity of 4 PSU for at least two months if it receives a flush of 5PSU after one month (Blum 1922). The larvae are the weakest link in the life cycle, and the adults can seal their borrows and survive for at least three weeks.

# 5 A step by step manual for ArcGIS model building and implementation

**The ArcGIS model**
One of the main objectives of this work is to build a model that can deal with the modelled environmental parameters of the Baltic Sea mentioned in the previous section, namely salinity, temperature, oxygen contentand current. The model covers the years 1980 to 2008 for the hind cast parameters, and the years 2009 to 2020 for the predicted environmental parameters.

**Environmental data preparation**
All data sets must be prepared for ArcGIS. If the dataset is in an Excel table, save the file as a comma separated text file (*.txt). The dataset should contain information on date, environmental layer and coordinate values as shown in table 4.

The environmental data sets represent two water column positions, one near sea bottom data set and the other for top layers. The top layer parameters were equivalent to an average of three top layers in the model. The upper layer is 5m thick, the next two are 2m thick each. This means the top layer represents a depth 9m from the sea surface. The bottom layer represents the last layer in the water column facing the seabed.

The data points represent weekly averages of the environmental parameters. In a simple mathematical calculation, one can calculate the number of data sets to be

| Date | Variable | Longitude | Latitude |
|---|---|---|---|
| 01/01/2009 | 23.75601 | 13.07942 | 65.71054 |
| 01/01/2009 | 24.45622 | 12.47545 | 65.63952 |
| 08/01/2009 | 18.62801 | 11.72542 | 54.51627 |
| 08/01/2009 | 18.88169 | 11.5558 | 54.49561 |
| 08/01/2009 | 19.13506 | 11.85552 | 54.47442 |

*Table 4: In the date column one can see the weekly change from the 1st of January to 8th of January.*

processed. There are 29 years of hind cast data sets, 52 weeks in each year, 2 different depths (top and near sea bottom) and there are 4 parameters to be processed. Therefore a monthly average was used instead of a weekly average because a general variation in the data rather than a spontaneous variation is required in this work. Repeating the mathematical calculation, it may be seen that:

29 x 12 x 2 x 4 = 2784 data sets handling operation.
In the same context there are 12 predicted years (2009-2020) which yields

12 x 12 x 2 x 4 = 1152 data set handling operation.

This gives a total of 3936 data set operations. An innovative method in ArcGIS has to be adopted to handle such a large number of data sets and process them within the limited period of the project (two years).
The partners agreed on using the ArcGIS as a data handling and processing platform because of its versatility, its large number of applications and spatial processing of data. The geographic coordinate system chosen for data presentation was the WGS84 and the projection was the UTM zone 34N.
An ArcGIS Model builder example is shown in figure 12. It is composed of an input project data set (in XYZ format) which represents the modelled environmental layers, a tool for re-projecting it into the new coordinate system, a ‘variable’ which

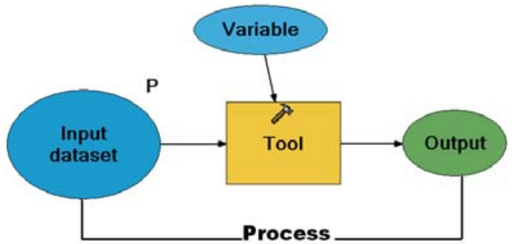



*Figure 12: An example of Model Builder used in the project shows a full process.*

permits the user to change the projection into the desired one, and then the output projected layer is derived. This is one process in the model. Other processes can be added, or attached, that include other types of tools which serve the required output of the model. Instead of processing each environmental layer alone, a suite of layers can be added to the input dataset and the model will handle all of them sequentially and process them.

An example of one main processing model used in this work is shown in figure 13. This model was built to process the Top Layer environmental data sets which are the top water column salinity, temperature, oxygen concentration and current.

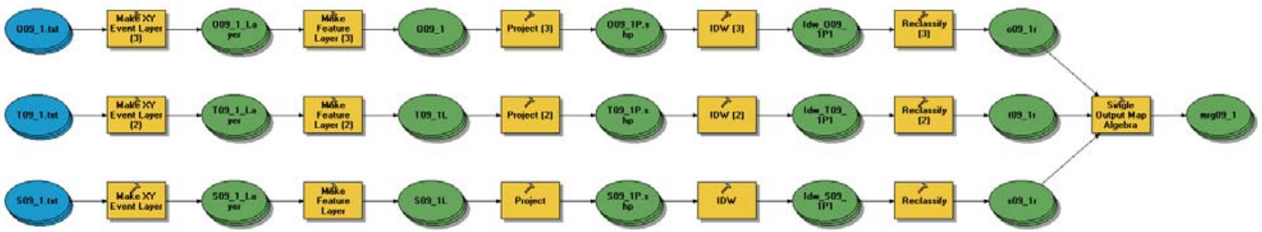



*Figure 13: Model for merging environmental layers.*

The algebraic addition of these data sets yields the final map of a particular year, this map is referred to as 'merged map'. The step-by-step guide how this model works is in the following chapter.

**Guide to building a model in ArcGIS**

The concept of geoprocessing is based on a framework of data transformation. In geoprocessing one takes an input dataset, performs an operation on that dataset, and then obtains an output dataset which can also be seen on the same platform. A suite of geoprocessing operations can be performed on different data types, the choice of which is governed by the required output and the purpose of the work. Geoprocessing is one of the most important aspects of a GIS because it provides the necessary tools to perform data analysis, conversion and management. It can be as simple as converting raster data set to feature class and can also cover more complicated operations for example finding a possible answer to multiple spatial questions such as 'how can this variable vary with time' and 'how much does this variable affect the neighbourhood'. Geoprocessing can be performed in four different ways; it can be accessed through the tool box, it can be interactively typed in the command line window, used in script environment like Python, or can be worked with in ModelBuilder to build a GIS task-based workflow, (fig. 14).

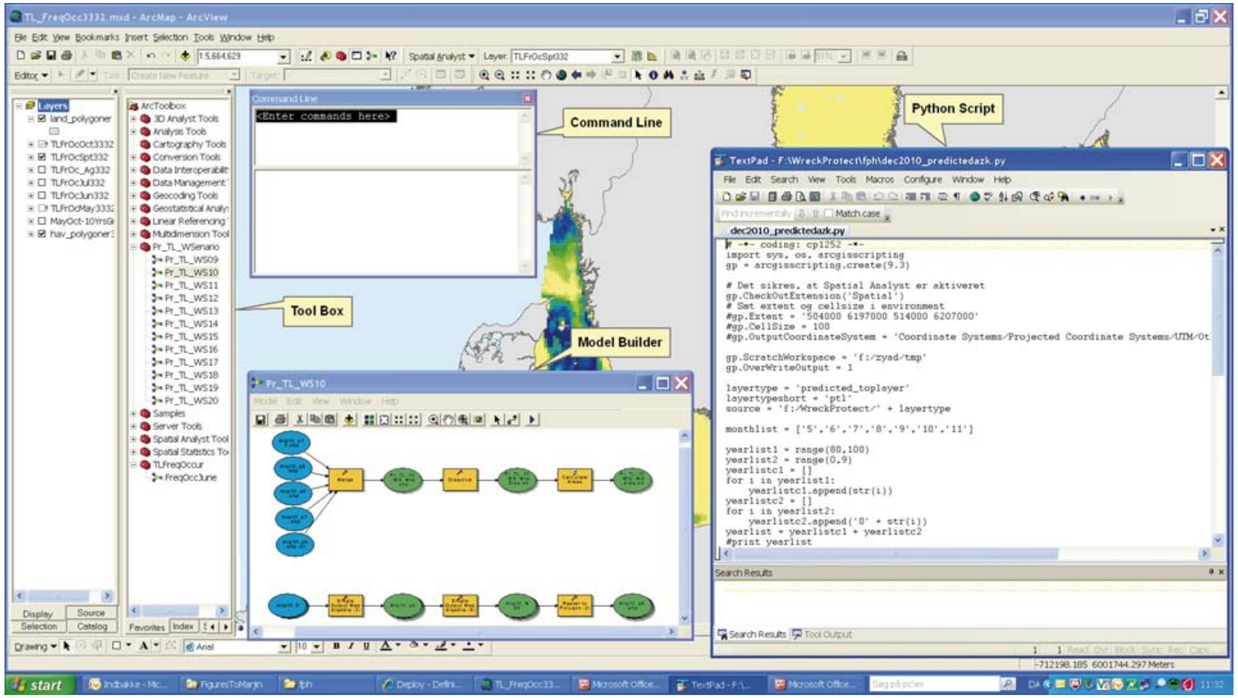



*Figure 14: Geoprocessing tools in ArcGIS.*

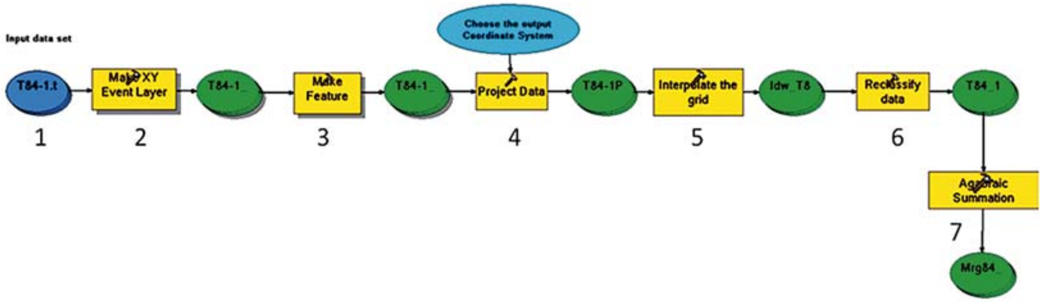



*Figure 15: Part of the model for merging of environmental data layers. The numbers 1, 2, 3 etc are step numbers, follow the text for more elaboration.*

**The model builder**

A model in general is a way to represent and simplify the reality, thus creating a manageable platform for processing and viewing the real world factors that were included in the model. In ArcGIS the model is displayed as a model diagram. The model builder enables the automation of the work flow in the geoprocessing operation by stringing processes together in the model diagram that will execute in sequence when the model is run. This reduces the processing time considerably, especially in complex models where a large number of geoprocessing operations takes place.

An example of the model produced by ArcGIS is shown in figure 15. It is composed of an input projec data set (in XYZ format) which represents the modelled environmental layers, a tool for re-projecting it into the new coordinate system, a 'variable' which permits the user to change the projection into the desired one, and then the output projected layer is derived. The other process will perform a gridding or interpolation of the projected data sets to a predefined grid size, then the data set will be classified into the desired classification and finally all data sets are merged algebraically together to produce the final product. The next chapter will give a step-by-step guideline for the building of this model.

A Model Builder Toolbar is shown in figure 16.

*Figure 16: Model Builder Toolbar.*

**How to create a model in ArcGIS?**
First create a new ArcToolbox where you can save the model. Right click the ArcToolbox heading and choose 'New Toolbox'. A new toolbox will be created in the Toolbox TOC. Here you can change its name. This tool box will be automatically stored in D/Document and Setting/'your name'/Application Data/ESRI/Arc Toolboxes/My Toolboxes. Right click on the new toolbox you've created and choose New/Model. A model window will be opened. Now the model is ready to be built. Remember to give the model a name and save it.

You can also create a new model by left clicking on the model icon, a model window will open, click Model/Model Property and change the model name to your choice. Then save it. This requires a Model Box to have already been created, navigate to the one you have created, as shown above and Save.

1 To open the model builder window when you want to start your model building again, click on the Toolbox you've created to see its content, right click the model icon in your own toolbox, click *Edit...* and the model builder window opens. Here you can input the text file you have prepared for geoprocessing. The input file is added to the model builder by clicking the *Add Data or Tool* button on the Toolbar. In the model builder the inputs (the *txt.file) will be shown as blue circles (Fig. 15, Step 1). The tools in the model are in a yellow square and the output layers are in a green circle. After the model is successfully run there will be a shadow on the tool square and the output circle.

2 Open the toolbox **Data Management Tools**, go to **Layers and Table Views** and drag the tool **Make XY Event Layer** into the model builder, (Fig. 15, Step 2). Connect this tool to your text file by clicking on the Add Connection button , click and drag from the txt file to the tool; you will notice the tool colour becomes yellow. ***This connection tool should be used with every added operation in order to connect it with the previous one***. Double click on the yellow square and check that it's filled in correctly. Remember to set the Spatial Reference to the input data Geographic Coordinate System. Give the output layer an appropriate name and save it.

3 The next step is to create a feature layer from the first output. Go to the toolbox **Data Management Tools** and the ***Layers and Table Views*** and find the tool ***Make Feature Layer*** and drag it to the model builder window, (Fig. 15, Step 3). Remember to give the output a short name. Run this step (by clicking on the Run button or go to Model/run). When you press run, the tool will change colour to red and when the run is successefully finished the green output circle gets a shadow.

4 The next step is to re-project the feature layer (Fig. 15, Step 4). This step could be neglected if the original data set is in the same coordinate system that you are working with. The tool for this step can be found in the **Data Management Tools** toolbox under ***Projections and Transformations – Feature – Project***. Drag the ***Project*** tool to the model builder window. Open the *Project* tool by double clicking on the square. The square is not yellow yet because it needs to have an output coordinate system. Again give the output feature layer a short and indicative name. You can right click at the project tool and choose Make Variable/From Parameter/Input Coordinate System, a blue circle will appear. Click in this circle and input the required coordinate system to which you want to convert your data to.

5 The next step is the interpolation (Fig. 15, Step 5). The IDW interpolates a surface from points using an inverse distance weighted (IDW) tenique. Go to the toolbox **Spatial Analyst Tools** and select the ***Interpolation*** toolbox and drag the tool ***IDW*** to the model builder window. Open the IDW tool by double clicking and fill in name for the *Z value field* give the name of the variable you would like to interpolate and choose an appropriate Output Cell Size (250m in our model), use Power 2 and search radius, Fixed, with Distance 12000 and Minimum number of points to be 1. The output is a gridded raster file.

**6** The last step before the merging of all the model parameters (e.g. salinity, temperature, oxygen and current) is to reclassify the raster output (Fig. 15, Step 6). This tool reclassifies the values in the input raster to the desired classification order. **3D Analyst (or Spatial Analyst Tool)** toolbox – ***Raster Reclass*** toolset – ***Reclassify*** tool. Connect the tool and double click on it and choose the **Reclass field**, **New Values** of the classification, this is done by clicking on **Classify** and choosing the Method , number of **Classes** and change the **Break values** manually then OK. Give the **Output raster** name and click OK.

**7** The last step is a ***Single Output Map Algebra*** expression (Fig. 15, Step 7). This tool merges all the model reclassified raster layers of current, oxygen, salinity and temperature by adding these layers algebraically together. The output is a raster of composite grid of the result from the addition operation. Each pixel has a specific cell size defined by the operator and a code which reflects the different classes of the merged data layers, see figure 6. This code can be translated into an environment for the larvae.
This tool can be found in the **Spatial Analyst** toolbox – ***Map Algebra – Single Output Map Algebra***. The map algebra expression is as listed below:

(S80_4r * 1000 + T80_4r * 100 + O80_4r * 10 + c80_4r * 1) = xxxx

In this scenario the code consists of four digits and represents four, merged input layers.

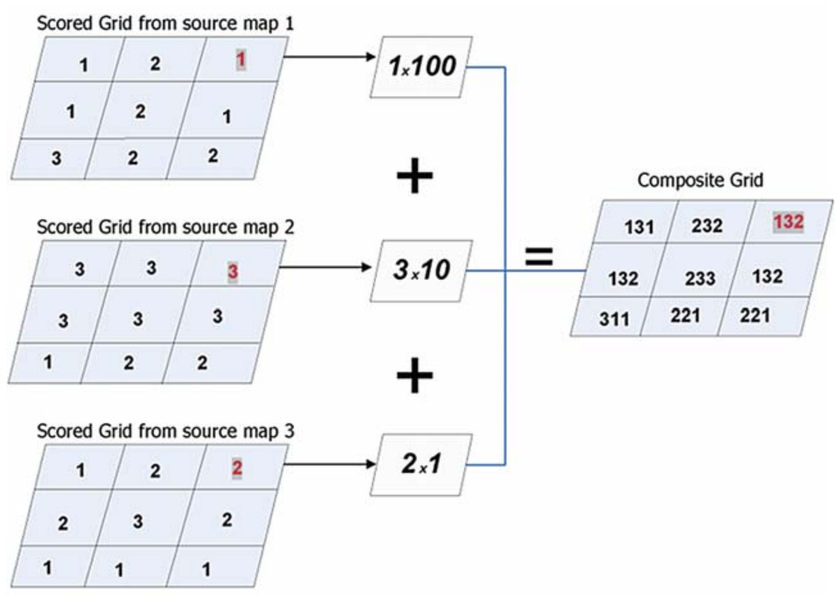



*Figure 17: The concept of the tool Single Output Map Algebra.*

**Model builder application**
The model shown above is used to delineate 'Hot Spot' positions where the probability of having the shipworm attack is high. To do that all datasets must be included in the analysis, a procedure that can take a considerable period of time if each operation has to be repeated 12 times (for each month) a year and for 40 years (1980 -2020). Using the model builder is an advantage in this case.
All the relevant data sets can be added to the model in the building stage. This is done when you first start building the model by right clicking on the input txt file (with the blue circle), choose **Properties** and click to choose **A list of value**s and click OK, you will notice that the txt file blue circle is now a multi-layer circle. Double click on this txt dataset to open and use the **+** sign to add the datasets required (or the ***X***

sign to delete the unwanted ones), click OK. Go to each operation (yellow rectangles) and make sure that the names of the output files are correctly written if not, correct the names manually.

**Limitations of the model and the outcome:**

**i** The technical limitation to the model is the manual inputting of the file names during the geoprocessing operation. As explained previously, this only happens when multi-layers are imported to the model such as salinity datasets from a series of years. In such cases, each salinity layer should be manually given a name otherwise all layers will have the same name. We believe this is a bug in the ESRI program and are currently discussing this with the software company. We are sure that this minor problem will be solved quickly.

**ii** The modelled environmental parameters, Salinity, Temperature, Oxygen, and Current have a spatial resolution of 3nm in the western part of the Baltic and 9nm in the rest of the Baltic. This is a very general resolution which yields a moderate number of Hot Spots. High resolution data is required to investigate areas around the existing ship wrecks in greater detail.

**iii** The spatial extension of the modelled data sets does not cover the entire Baltic Sea up to the shoreline, as it depends on the depth step factor which cannot describe the very shallow coastal region. These regions could be considered as good ‘shelter’ for shipworms. Data sets with full extension will reveal these areas, so a more precise Hot Spot distribution map can be obtained.

**iv** The published data for the shipworm *T. navalis* is very limited, especially for the Baltic Sea region. Accurate categorisation of the environmental parameters which are used to predict the Hot Spot areas require expert judgment and estimations based on published and reliable results.

**v** The current data obtained was scalar and lacked direction. Such data cannot result in calculations to estimate accurately the probable dispersal of larvae over a specific period of time and in a specific location.

**vi** Shipworm can also be spread by ballast water, floating pieces of wood, human activities etc. These factors were not taken into account in the model, but could be added to the confidence map as external factors in shipworm spread.

# 6 The maps

As shown in the previous chapters the environmental parameters influencing the shipworm *Teredo navalis* were imported to GIS and a model built to geoprocess these data sets, merge them according to predefined classification criteria and present them spatially. The final output comprises a suite of merging scenarios ranging from levels of possible attack by shipworm larvae to the lethal limits. The spatial extent of a certain scenario in this model is often dependent on one influential environmental parameter within the merged group. Using one example to clarify the process, it can be seen in figures 18, 19 and 20 that the top layer merges data (salinity, temperature and oxygen) as well as the top layer salinity and temperature. It is assumed that oxygen has little influence on the resulting merged layer. This assumption is justified as the top layer gets mixed most of the time so the oxygen content is almost constant.

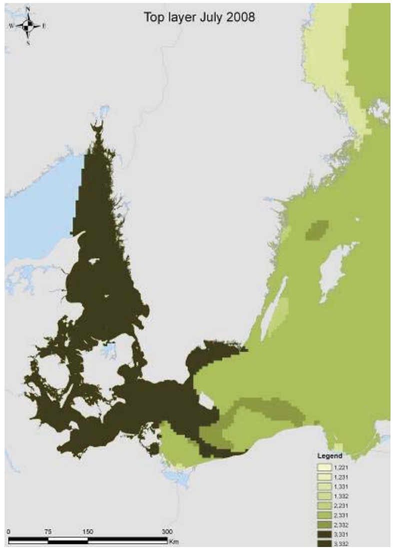



*Figure 18: Top layer merged parameters, July 2008.*

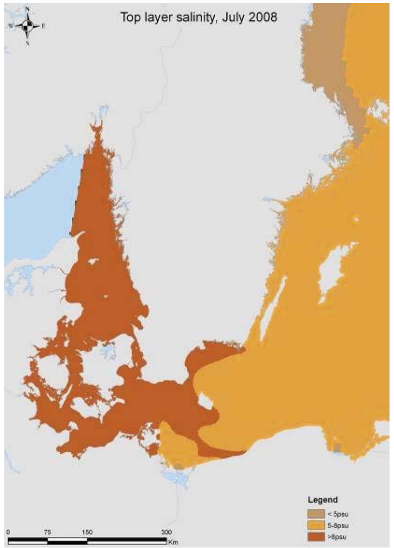



*Figure 19: Top layer salinity, July 2008*

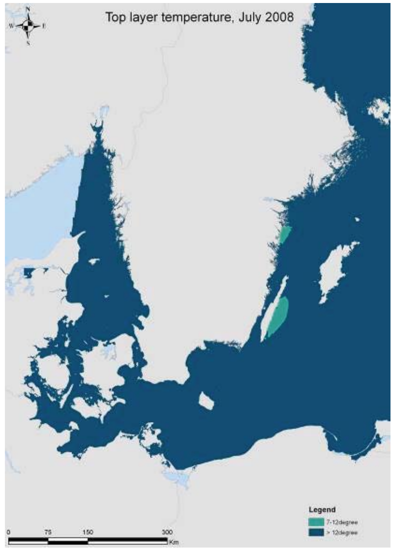
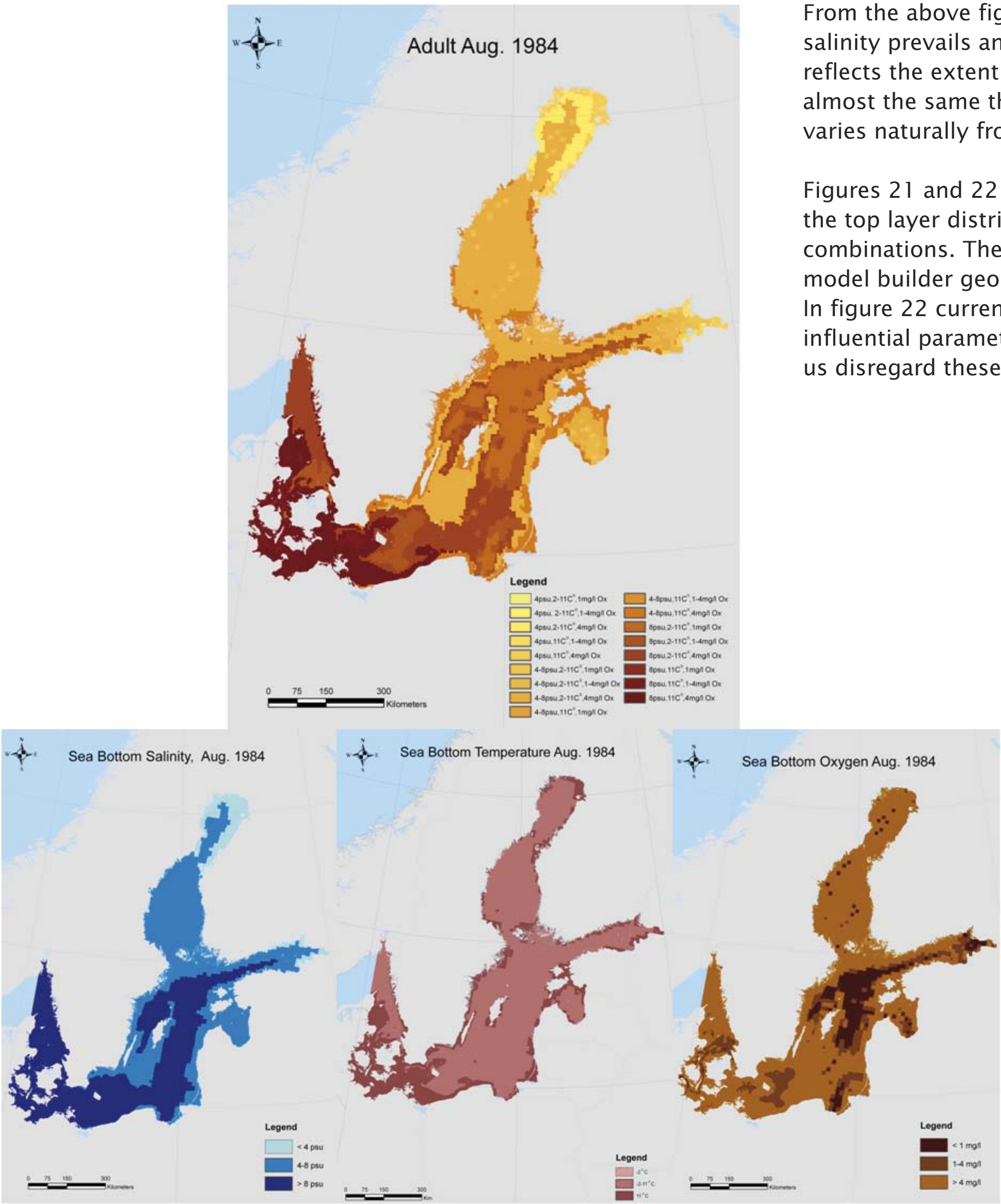



*Figure 20: Top layer temperature, July 2008.*




From the above figures it can be noted that the influence of salinity prevails and the final combination or merged result reflects the extent of the salinity layer only. The temperature is almost the same throughout the area. The spatial distribution varies naturally from month to month and from year to year.

Figures 21 and 22 show general maps for the bottom layer and the top layer distribution of different environmental parameter combinations. These combinations were performed in the model builder geoprocessing stage mentioned earlier.
In figure 22 current was also taken into account as a possible influential parameter. However lack of current direction made us disregard these data at a later stage of the project.

*Figure 21: Bottom layer (adults) combined environmental parameters spatial distribution as well as maps of these parameters in August 1984.*

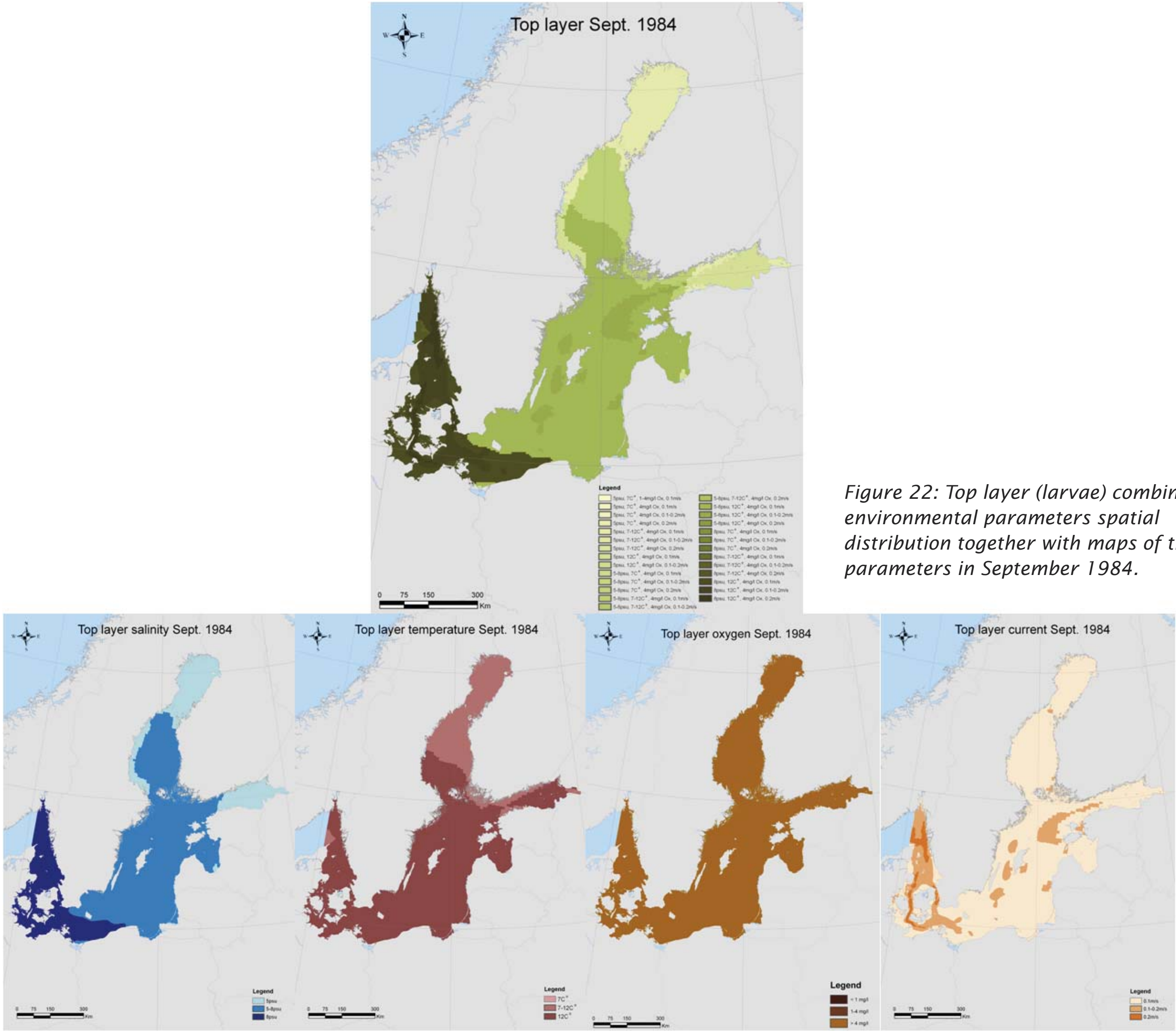



*Figure 22: Top layer (larvae) combined environmental parameters spatial distribution together with maps of these parameters in September 1984.*

# 6 Maps

The frequency of occurrence of certain combination scenarios of the environmental parameters for the top layer are presented in figures 23 to 25. Scenario number 3332 (current included) represents the combinations of salinity > 8, temperature > 12, oxygen > 4, and current 0.1 – 0.2. The figures show the expected spatial variation of the possible scenario for shipworm larval settlement between May, July and September over the period 2009-2020.

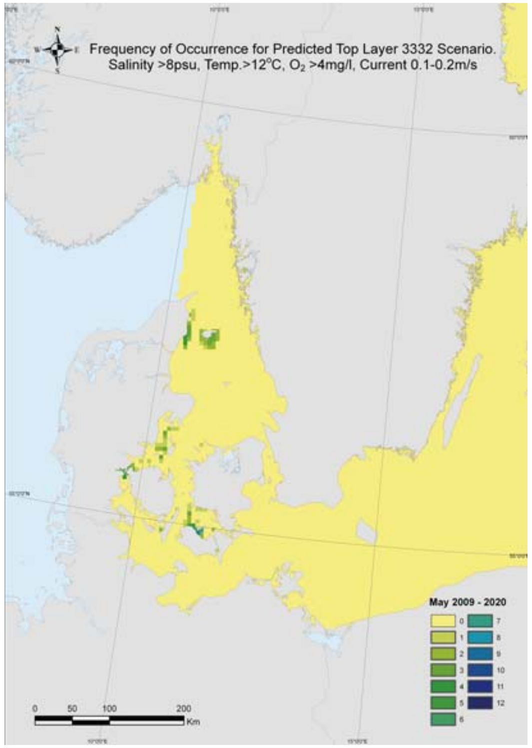



*Figure 23: Top Layer frequency of occurrence May 2009 -2020.*

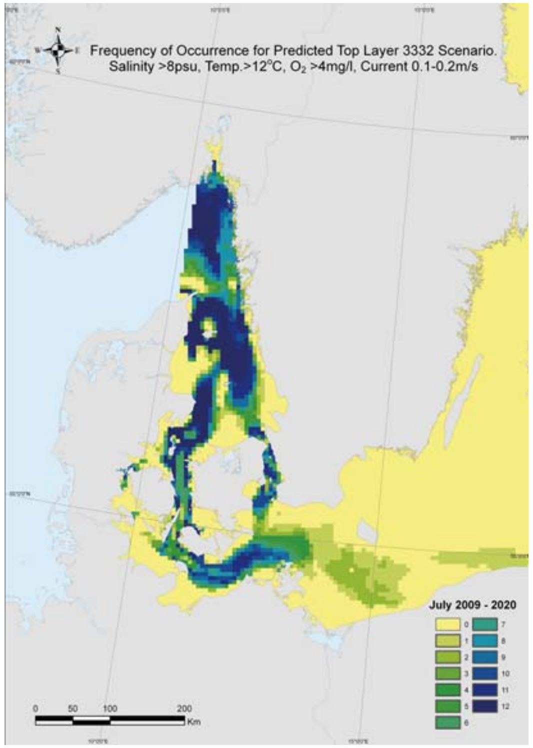



*Figure 24: Top Layer frequency of occurrence July 2009 -2020.*

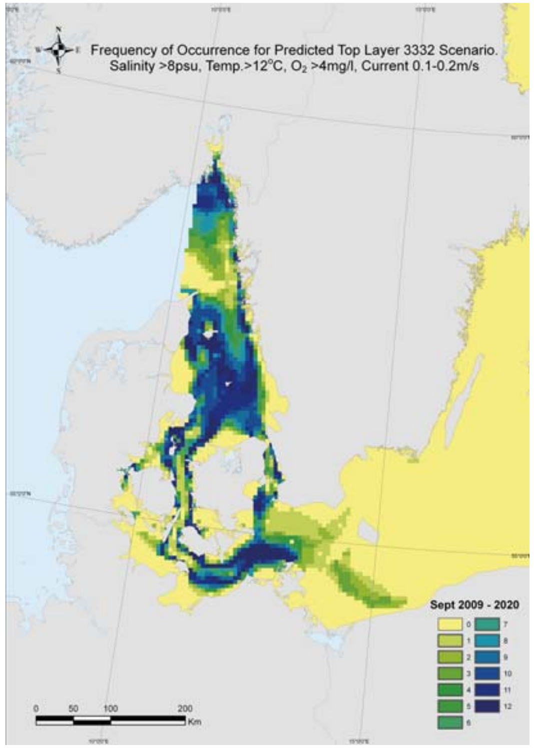



*Figure 25: Top Layer frequency of occurrence September 2009 -2020.*

Figures 26 and 27 show the frequency of occurrence of the same scenario as above for October over two periods 1980-1999 and 2008-2020. The figures show the increase in the spatial extension of this scenario across the whole area and towards the east in the Baltic Sea.

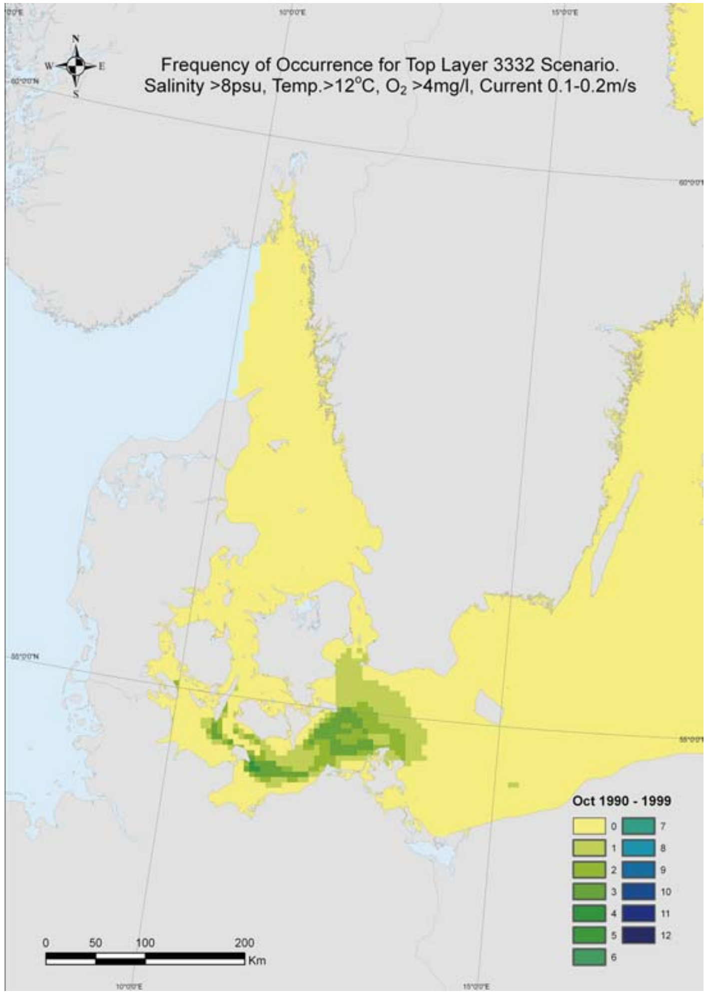



*Figure 26: Frequency of occurrence October 1990-1999.*

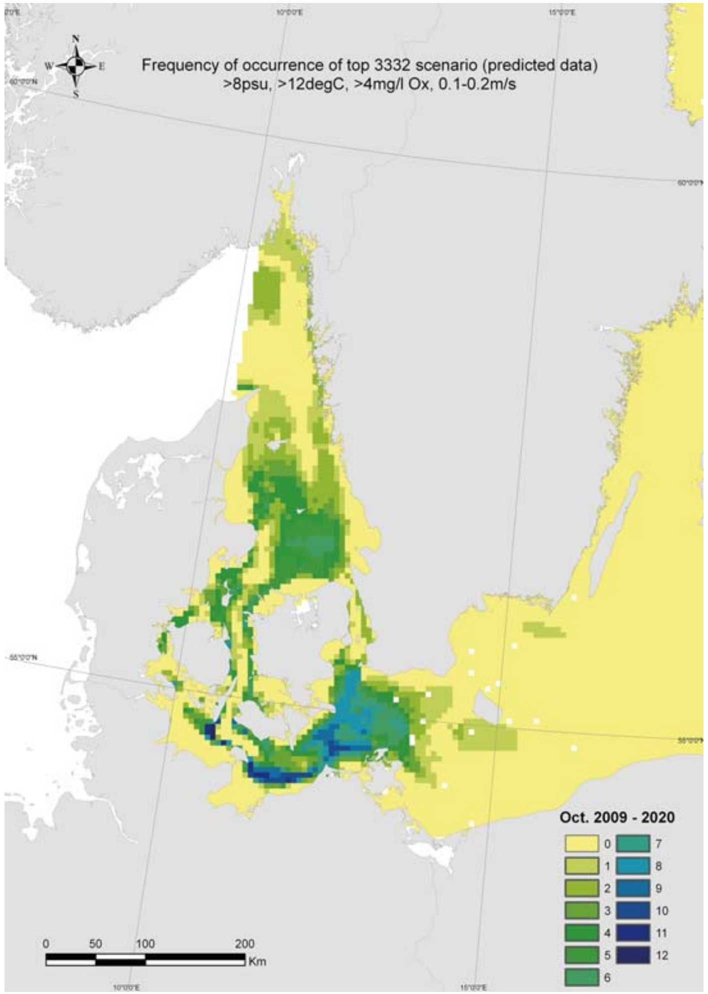



*Figure 27: Frequency of occurrence October 2009-2020.*

Figures 28, 29 and 30 show the annual variation of the top layer combined parameter scenario (still with current included) for June – September in 1986, 1997 and 2000. The spatial extension changes each year due to the environmental parameters dynamic variation. An area which is very susceptible to shipworm in one year may not be susceptible next year. However, there are some permanent regions in the Baltic where these favourable conditions are almost permanent.


*Figure 28: Top Layer 3333 scenario June-September 1986.*


*Figure 29: Top Layer 3333 scenario June-September 1997.*

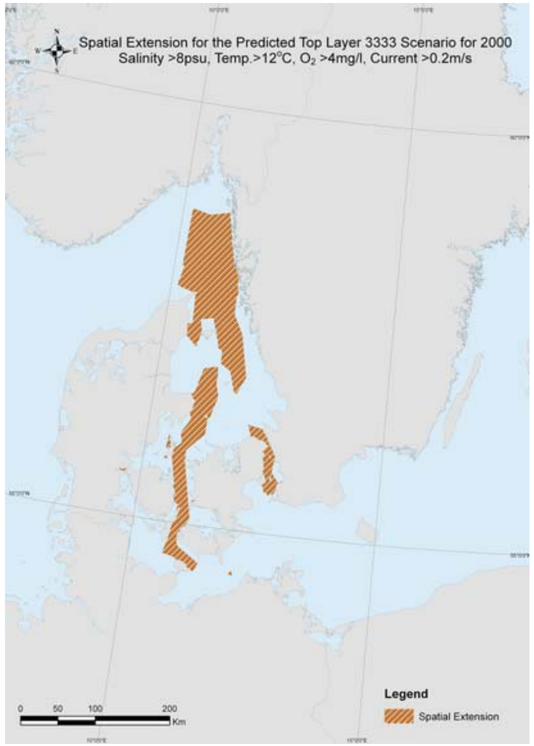



*Figure 30: Top Layer 3333 scenario June-September 2000.*

# 7 Simplified maps of potential *Teredo* spread in the Baltic

Underwater cultural heritage is challenged by difficulties when managing spread and detection of shipworm. The most obvious is that shipworm is not visible with the naked eye. WreckProtect's approach makes it possible to overcome this problem by launching the ArcGIS tool based on the environmental requirements of the *Teredo navalis*. Based on the results from the ArcGIS Model, WreckProtect has designed a few maps to inform the general public. These maps can be seen below and are digitally downloaded through www.wreckprotect.eu.

The 'public maps' are based on maps produced by the model, like those in figures 31 and 32. In these maps salinity, temperature and oxygen were taken into account. Current has been disregarded due to lack of information about current direction. As one can see, these maps contain a lot of detail. However, we have to be aware that these variations are just variations in the presence of the different favourable parameters. These are calculations and not, so to say, facts to show the actual distribution of shipworm. To avoid confusion we have simplified these maps. By carefully studying all results from measurements taken between 1980 and 2008 and the results from the model 2009 to 2020, we have selected the maximum extent of the favourable scenarios possible metamorphosis and reproduction of the adult *Teredo* (figures 34 and 35) and for living conditions of the larvae (figures 37 and 38).
Figure 36 shows a combined map for the ideal environment for the adult *Teredo* (bottom layer) as measured between 1980 and 2008 and (as a result of the modelling) of 2009-2020.
Figure 39 shows a combined map for the ideal environment for the *Teredo* larvae (near the surface) as measured between 1980 and 2008 and (as a result of the modelling) of 2009-2020.
If we combine all the information collected by analysing the species *Teredo navalis*, the environmental parameters and the result of the model, then we come to a possible danger area for the spread and attack of this shipworm in the Baltic.
Figure 40 shows us this area in red. The top of this picture depicts shipwrecks that have been discovered far away from the threatened area. These sites, like the Vrouw Maria and the Ghostwreck, are all in excellent condition. The bottom of the picture depicts sites that are under threat of *Teredo* attack. This picture has the function to raise awareness on the threat of *Teredo* attack underwater cultural heritage is facing in (a limited area of) the Baltic.

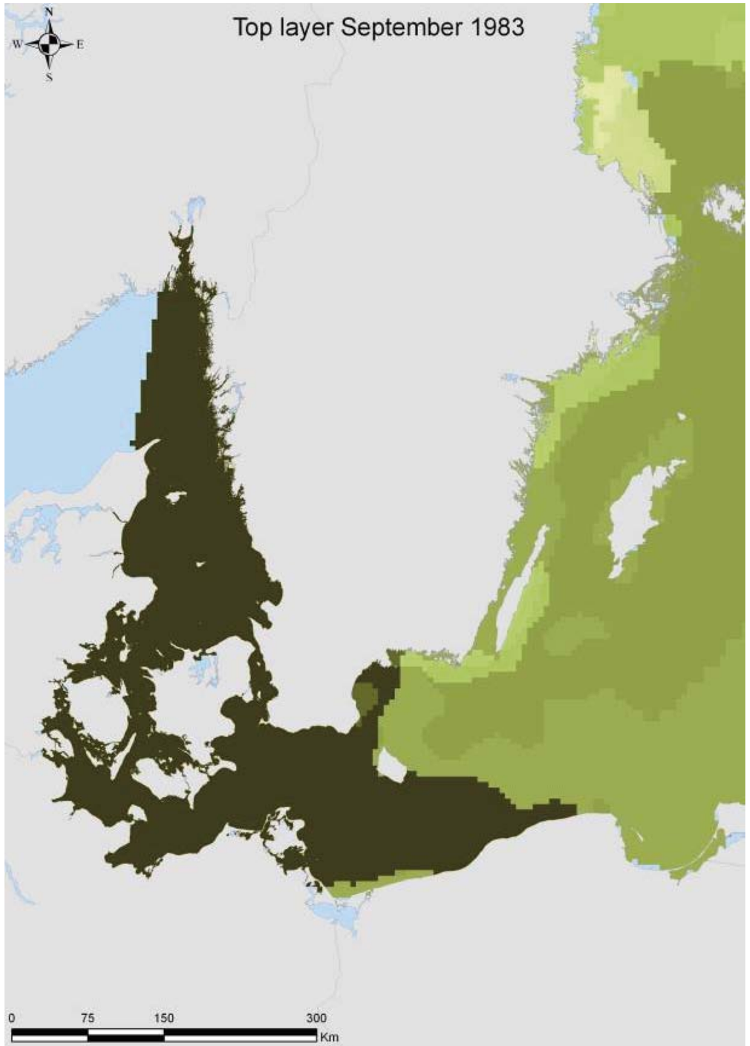



*Figure 31: Top layer Sept1983. Dark green: Hotspot region i.e. possible range for new shipworm* T. navalis *attack.*

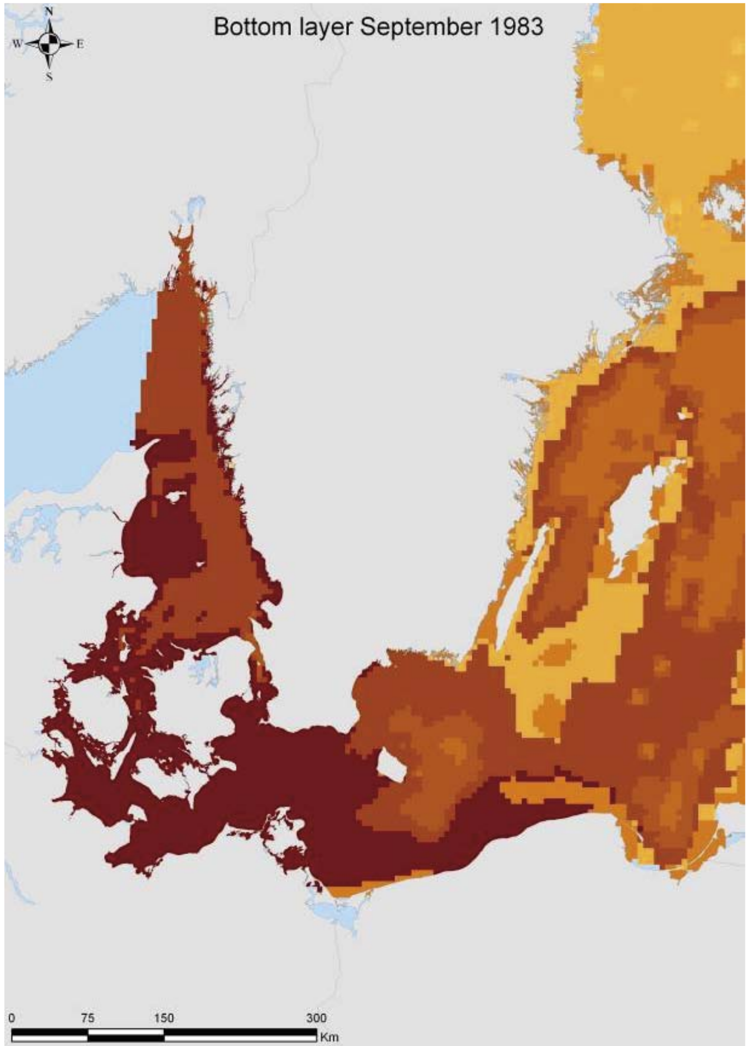



*Figure 32: Bottom layer Sept1983. Dark brown: Hotspot region i.e. possible range for new shipworm* T. navalis *attack.*

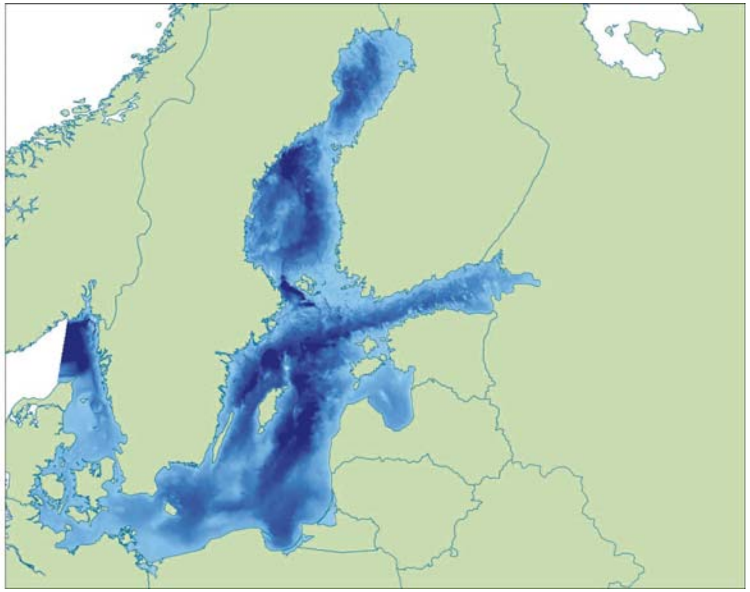


*Figure 33: The bathymetry of the Baltic Sea. Courtesy BALANCE project/RCE.*

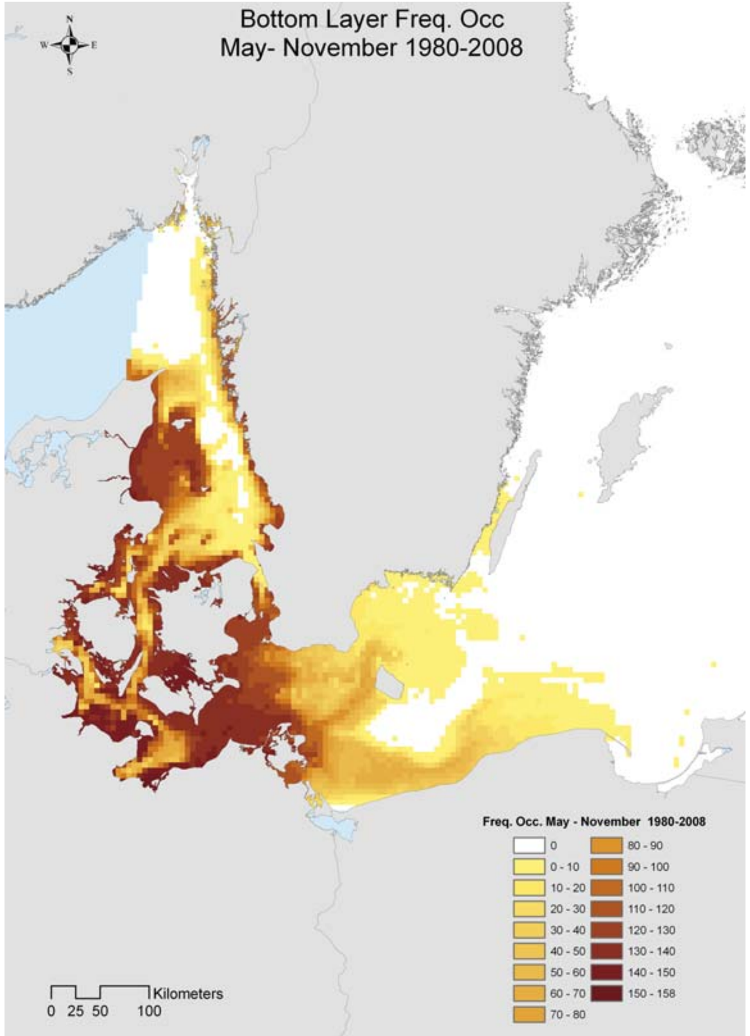



*Figure 34: Integrated hindcast map for occurence of the favorable scenario for the adult shipworm (Teredo navalis). Modelled environmental parameters near the seabed for the period May-November 1980-2020.*

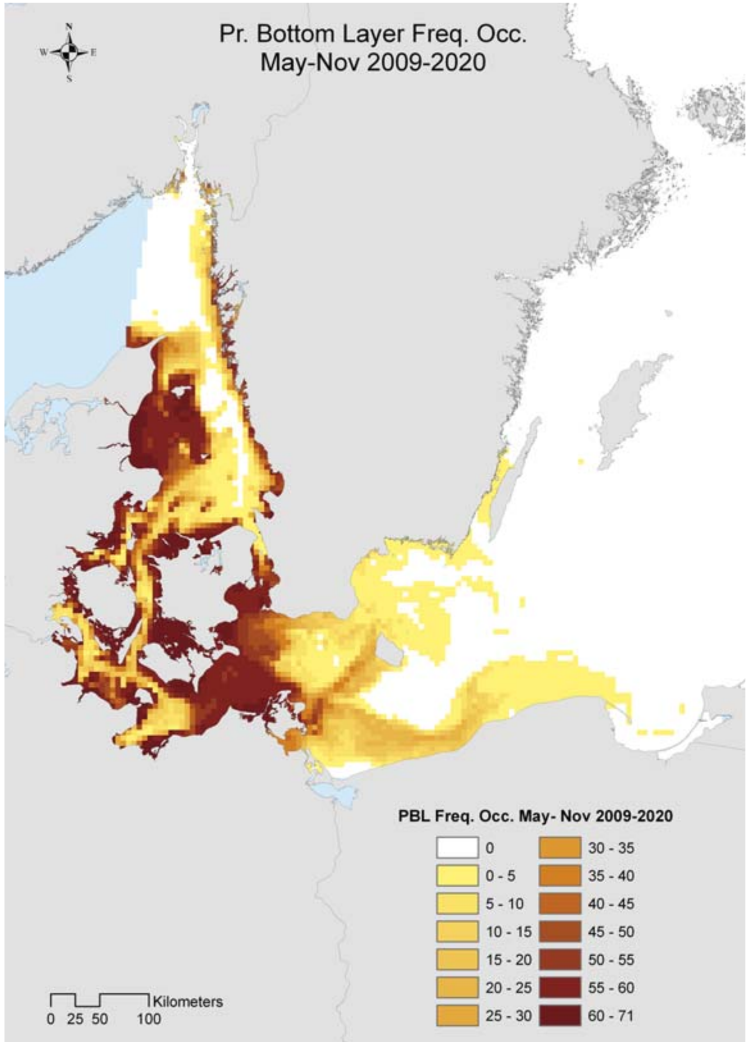



*Figure 35: Integrated forecast map for occurence of the favorable scenario for the adult shipworm (Teredo navalis). Modelled environmental parameters near the seabed for the period May-November 2009-2020.*

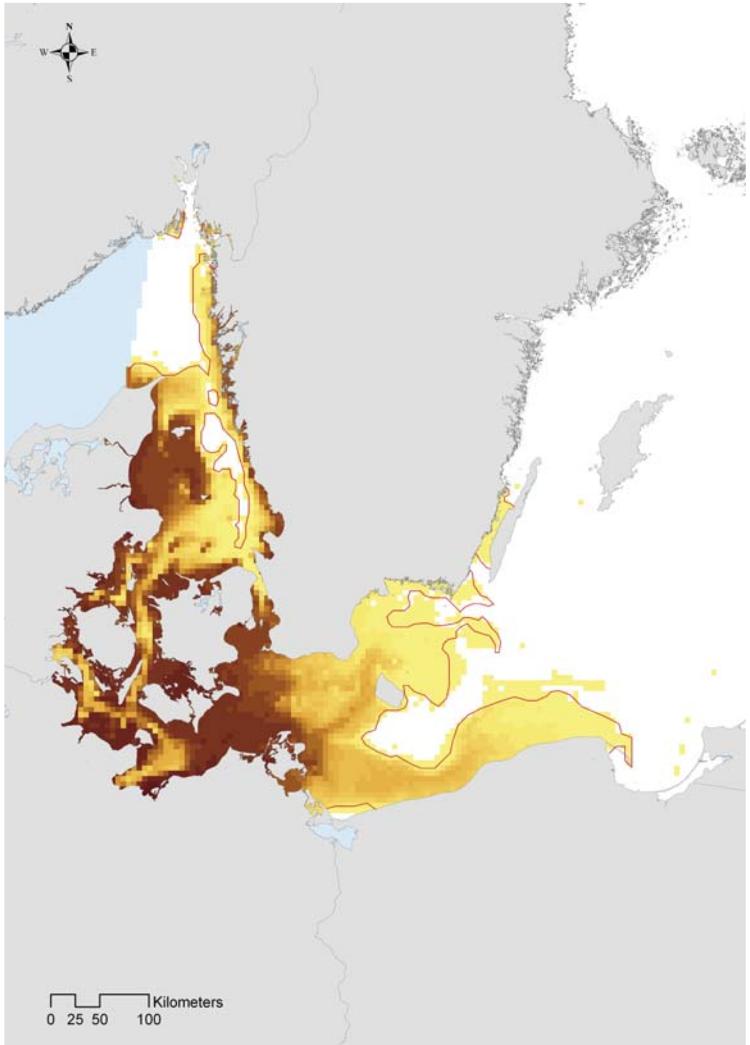



*Figure 36: Occurrence of the favourable scenario for the adult shipworm. And integrated map showing figure 34 (Modelled environmental parameters near the seabed 1980-2008) combined with the maximum possible favourable scenario modeled for the period 2009-2020. The red line represents outer boundary (figure 35).*

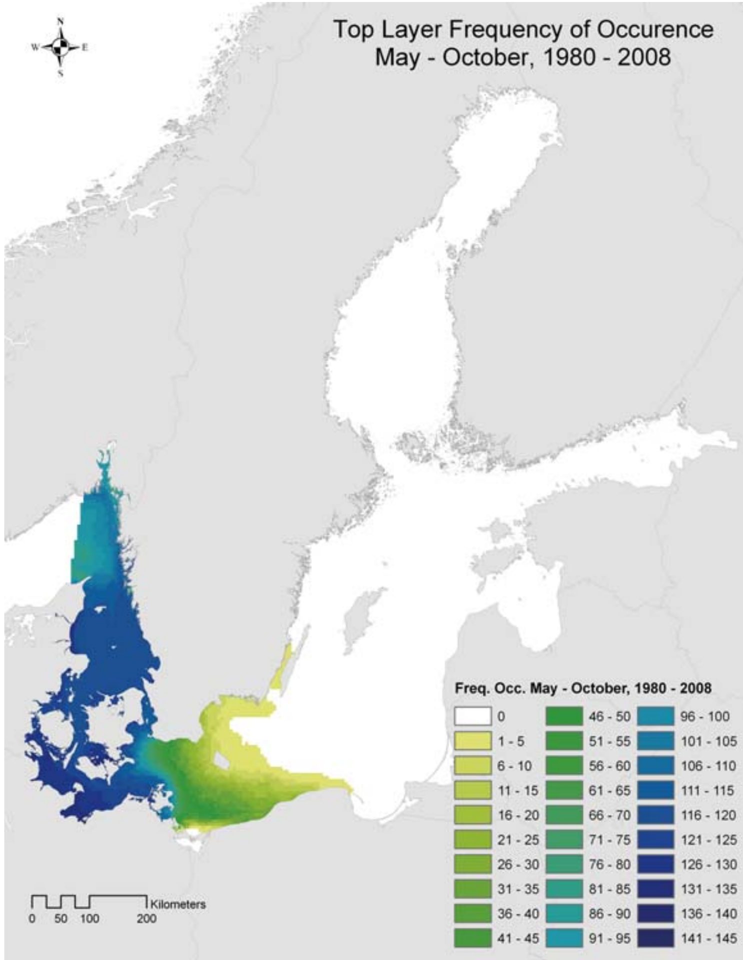



*Figure 37: Integrated map for occurrence of the favourable scenario for the larvae of Teredo navalis modelled environmental parameters in the layer near the surface for the period May-October 1980-2008.*

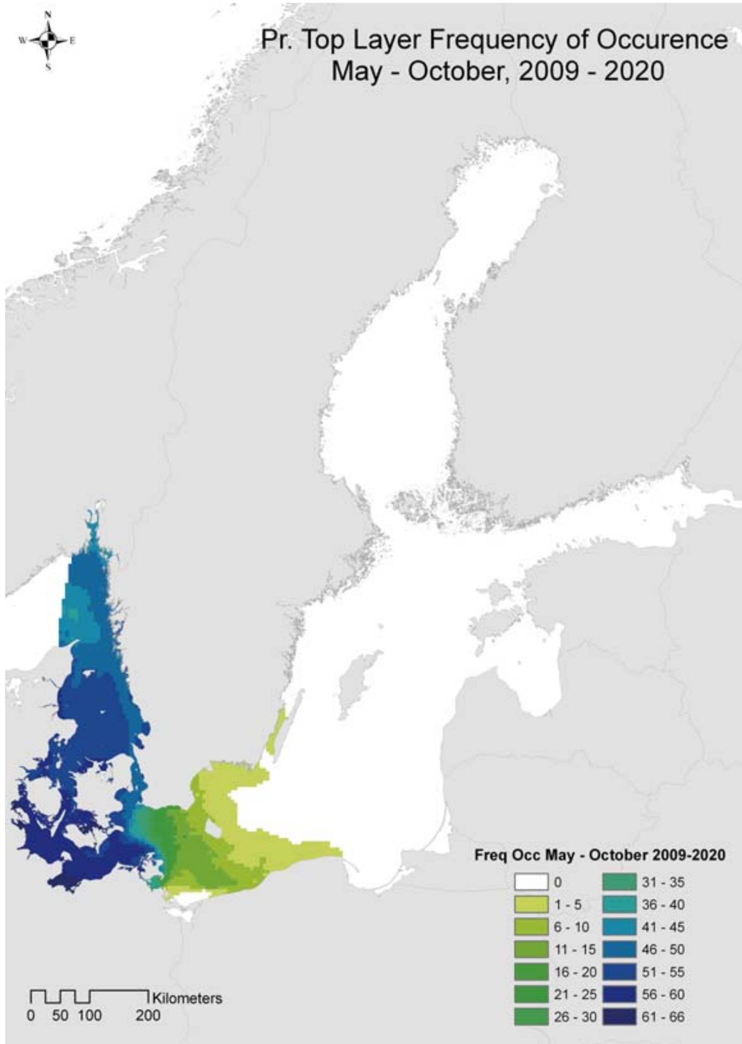



*Figure 38: Integrated map for occurrence of the favourable scenario for the larvae of Teredo navalis modelled environmental parameters in the layer near the surface for the period May-October 2009-2020.*

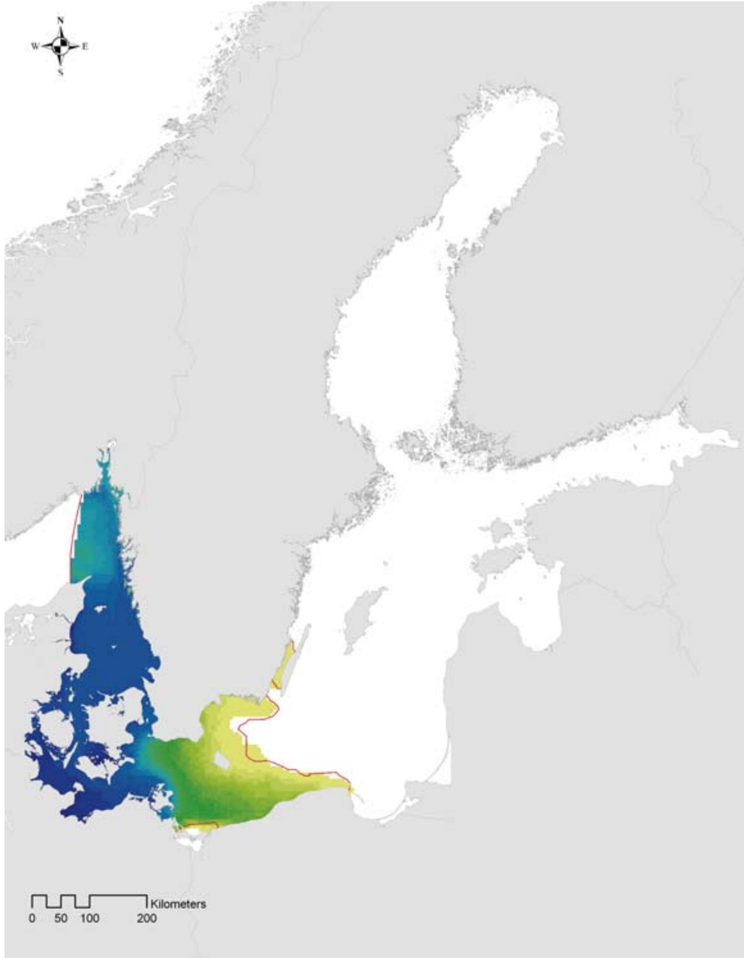



*Figure 39: Occurrence of the favourable scenario for the larvae of the shipworm (Teredo navalis). An integrated map showing figure 37 (Modelled environmental parameters in the layer near the surface for the period May-October 1980-2008) combined with the maximum possible favourable scenario (red line represents outer boundary) modeled for the period 2009-2020 (figure 38).*


*Figure 40: The maximum possible spread of Teredo navalis 1980-2020, based on modeled data and literature on the species environmental requirements (temperature, salinity and oxygen). This is a simplified map with combining information from figure 34 to 39. The idea is to visualize the area of threat by the shipworm (Teredo navalis). The photographs on the top are well preserved shipwrecks situated in a more northern part of the Baltic, free of Teredo navalis. From left to right: Dalarö wreck, Ghost ship and Vrouw Maria. The photographs on the bottom are, from left to right: Darss Cog, Greiffswald ship barrier and W23. These ships are, and will in future still be under threat.*

# 8 Using the maps in this guideline

The maps shown in this guideline will be made available by the WreckProtect Project as separate maps that can be down-loaded through the project website www.wreckprotect.eu. Also, the GIS maps and the required data behind the model will in future be integrated into another GIS model known as the MACHU-GIS. This GIS has been developed within the MACHU project (Managing Cultural Heritage Underwater) financed by the EU-Culture 2000 programme and completed in 2009. Its web page (www.machuproject.eu) will continued to be run by RCE ( partner of WreckProtect) and this is the reason for this decision. The MACHU GIS consists of several layers including the archaeological layer, research layer, legislative layer and a layer for historical maps. The WreckProtect maps will be added to a separate *Teredo navalis* in the Baltic layer in the GIS.
The GIS was developed in order to exchange data and information between countries and to have the opportunity to manage the underwater cultural heritage together on a cross disciplinary basis. For the Baltic Sea this is essential because it is almost completely surrounded by 9 countries and these countries have an important say in the management of the sea and its resources through territorial waters, contiguous and economic zones.

# 9 Conclusions

This guideline will help stakeholders taking responsibility for the long term preservation and protection of unique and high priority shipwrecks and submerged archaeological sites. The GIS tool enables end-users to continuously follow the 'shipworm decay potential' at important wreck locations, by updating the environmental parameters (salinity, oxygen and temperature) for the area. Data can be purchased from different companies or are available from other environmental projects related to the Baltic Sea. In this way physical protection or other measures to protect wrecks can be taken in sufficient time to avoid an invasion of aggressive shipworm which that can decompose wrecks within a few years.

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