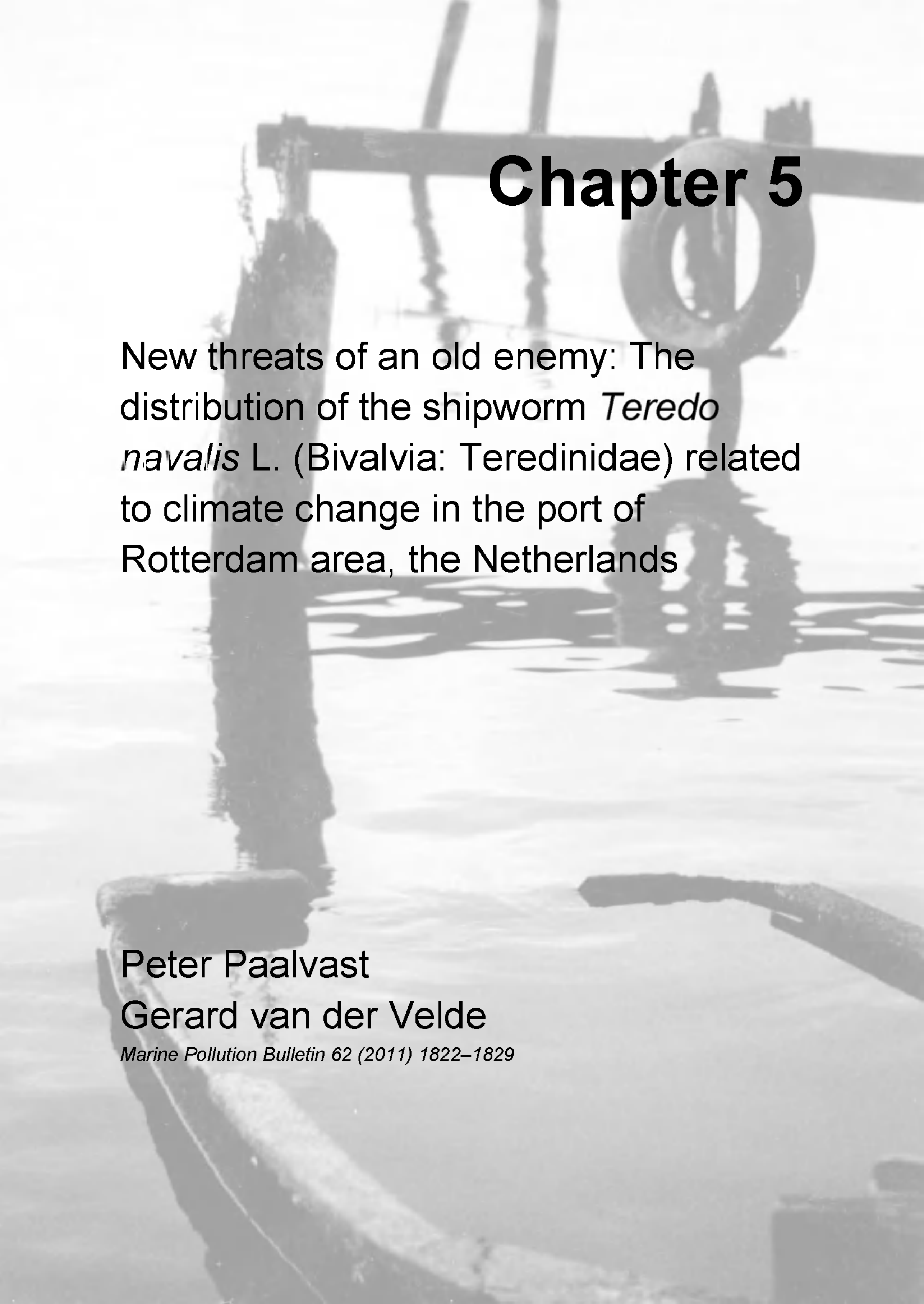

Chapter 5

New threats of an old enemy: The distribution of the shipworm *Teredo navalis* L. (Bivalvia: Teredinidae) related to climate change in the port of Rotterdam area, the Netherlands

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Abstract

The effects of four climate change scenarios for the Netherlands on the distribution of the shipworm upstream the Rhine-Meuse estuary are described. Global warming will cause dry and warmer summers and decreased river discharges. This will extend the salinity gradient upstream in summer and fall and may lead to attacks on wooden structures by the shipworm. Scenarios with a one and two degree temperature increases by 2050 compared to 1990 with a weak change in air circulation above Europe will lead to an increased chance of shipworm damage upstream from once in 36 years to once in 27 and 22 years, respectively, however with a strong change in air circulation, the chance of shipworm damage increases to once in 6 and 3 years, respectively. The upstream expansion of the distribution of the shipworm stream upwards will also be manifest in other Northwest European estuaries and will even be stronger in Southern Europe.

Introduction

Shipworms (Teredinidae) are wood-boring marine bivalves. The shipworm *Teredo navalis* L. appeared in 1730 in the coastal waters of the Netherlands and was described by Sellius (1733) as *Teredo marina*. Its origin is unknown, and the species is therefore described as cryptogenic by Hoppe (2002). In the successive years of 1731 and 1732, massive destruction of the wooden constructions that protected the dikes in Zealand and Westfrisland occurred (Vrolik et al., 1860). Authorities attempted to use tropical hardwoods and arsenic and to cover the wooden dike gates with iron plates and nails, but the only (very expensive) solution was changing the mode of dike construction. This began as soon as 1733 by defending the dikes with imported stones, and over the centuries, this has led to the "petrification" of large parts of the Dutch coastline. Later outbreaks of the species took place in the Netherlands in 1770, 1827, 1858 and 1859. Not only were sluices and dolphins in harbours upstream of the Rhine–Meuse estuary found to be infected in 1826, but quays also collapsed. Low river discharges resulting in increased salinity had created favorable conditions for the shipworm. The shipworm is still commonly found in Dutch coastal waters and enclosed salt water bodies in the Dutch Delta Area (Van Benthem Jutting, 1943, De Bruyne, 1994).

If shipworms encounter optimal abiotic conditions, they are able to destroy fir piles 15 cm in diameter in six weeks (Snow, 1917), and even 10 m long, 25 cm thick oak pilings can be turned into rubble in 7 months (Cobb, 2002). In 1995, shipworm damage in the US was estimated to cost approximately US$ 200 million per year (Cohen and Carlton, 1995). Over the centuries, many attempts to protect wood structures from shipworm attacks have more or less failed. They have used copper and lead plating, nails with large flat heads (Teredo-nails), paraffin, tar, asphalt, and paints. The most effective deterrent, creosote, has been banned in many countries because of its toxic and carcinogenic properties (Snow, 1917, Hoppe, 2002). Chemical impregnation with chrome copper arsenate (CCA) or borax (CKB) is widely used as a wood preservative and is effective, although this practice remains controversial among environmentalists (Hoppe, 2002).

The adult shipworm tolerates salinity conditions between 5 and 35 (Nair and Sarawathy, 1971) and thrives and reproduces at salinities of 9 and higher (Kristensen, 1969, Soldatova, 1961 in Tuente et al., 2002). Boring activity stops below a salinity of 9–10. Pelagic shipworm larvae survive at salinities as low as 6, and below that salinity level, pediveligers die within a few days (Hoagland, 1986). It was observed in Germany that a low salinity of 9 prevented the establishment of shipworm larvae (Hoppe, 2002). At water current velocities exceeding 0.8 m^1 s^{-1}, shipworm larvae can no longer attach to wood (Quayle, 1992). The optimal water temperatures for growth and reproduction range between 15 and 25°C. Spawning is initiated when the temperature rises above 11 to 12°C. These animals may breed from May until October (Grave, 1928). First year animals may reach sexual maturity in six weeks (Lane, 1959). Temperatures up to 30°C are tolerated. Boring activity decreases below 10°C and stops at 5°C (Roch, 1932, Norman, 1977). At temperatures near the freezing point, shipworms hibernate until the water temperature becomes favourable again.

The complete salinity gradient of the Rhine-Meuse estuary is present in the port of Rotterdam area, and a vital shipworm population exists in the large polyhaline harbours in the western region (Beerkanaal and Calandkanaal). *T. navalis* settlement in the port of Rotterdam area decreases with increasing distance from the sea floor in both test panels and beams (Paalvast and Van der Velde, 2011). This was also found by Scheltema and Truitt (1956) in test panels in coastal waters of Maryland in the US and by Tuente et al. (2002) in the harbours of Bremerhaven in Germany.

The situation in the Rotterdam port area, which is one of the largest ports in the world, can be used as a typical example of the estuaries of all large temperate rivers in western Europe. Various climate models (Van den Hurk et al., 2006, 2007, Boé et al., 2009, Diaz-Nieto and Wilby, 2005) used to predict the effects of global warming on the hydrology of these large rivers show, on average, a serious decrease in precipitation during summer and fall, leading to lower river discharges. Combined with an expected sea level rise, this will lead to an increasing salinity over large parts of the estuarine gradient (Beijk, 2008).

Therefore the following research question was formulated: What is the risk of shipworm damage (i.e. expansion of its distribution upstream) under present climate conditions and under climate change due to global warming?

Materials and methods

Study area

The port of Rotterdam is situated in the estuary of the Rhine and Meuse (Fig. 1). It stretches over a length of 40 kilometres and covers 10,500 hectares, 3,440 hectares of which are covered by harbour waters and 1,960 hectares, by rivers and canals. Under average conditions, with a Rhine river discharge at the Dutch-German border (Qbr) of 2200 m^3 s^{-1}, the complete salinity gradient from fresh to seawater is found in this part of the estuary. This salinity gradient moves downstream at ebb tide and upstream at floodtide. The hydrology of the area is strongly controlled by means of the drainage program for the Haringvliet sluices

(Fig. 1), based on the discharge of the Rhine at the Dutch-German border (Qbr). The degree to which the sluice gates are opened at ebb tide increases with increasing discharge of fresh water. To avoid salinisation upstream of Rotterdam, 1500 $m^3 s^{-1}$ of fresh water is directed to the port of Rotterdam area, i.e., the Nieuwe Waterweg (1300 $m^3 s^{-1}$) and the Hartelkanaal (200 $m^3 s^{-1}$). This flow of fresh water via the port of Rotterdam area can be maintained between a Qbr of 1700 $m^3 s^{-1}$ and 4500 $m^3 s^{-1}$. Below 1700 $m^3 s^{-1}$, the salinity gradient shifts landwards, while above 4500 $m^3 s^{-1}$ it moves seaward. At a Qbr of approximately 1100 $m^3 s^{-1}$, the Haringvliet sluices are closed completely, and both Meuse and Rhine waters flow into the sea at Hoek van Holland. The isohalines of the bottom water in the area under average and low river discharges (1000 $m^3 s^{-1}$) were calculated using the RIJMAMO model of Rijkswaterstaat (Bol and Kraak, 1998) (Fig. 2A; 2B).

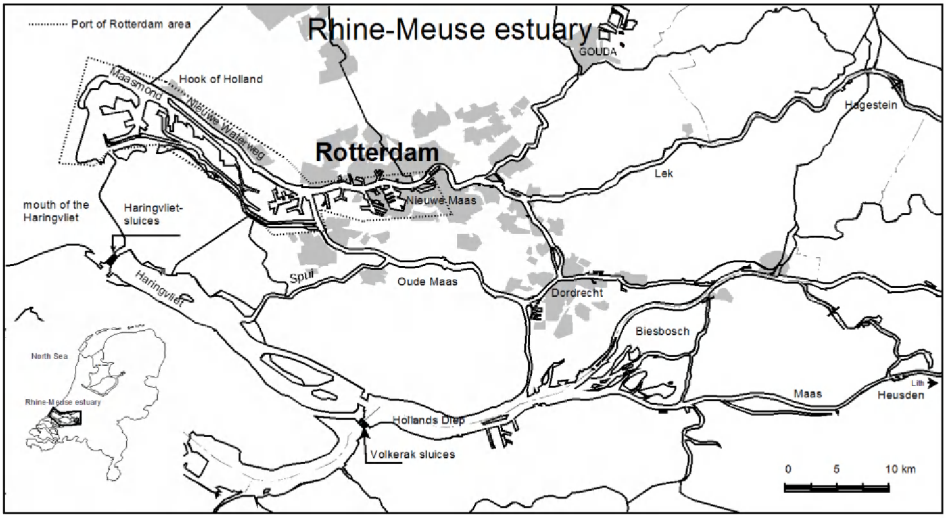

Figure 1 The port of Rotterdam in the Rhine-Meuse estuary.

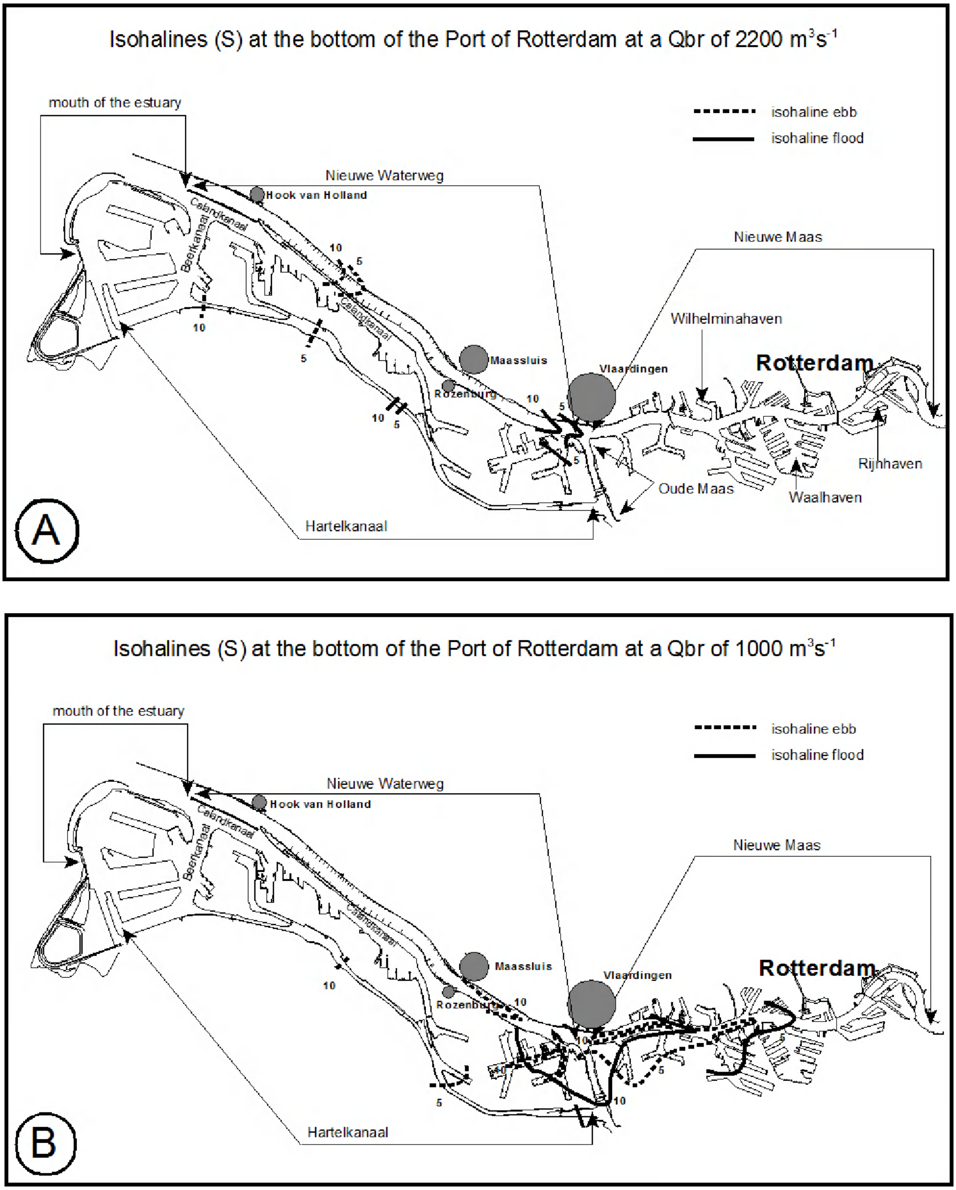

Figure 2 (A) The 5 and 10 isohalines during ebb and flood periods in the port of Rotterdam area under an average discharge of the Rhine at the Dutch-German border (Qbr) of 2200 $m^3 s^{-1}$. (B). The 5 and 10 isohalines during ebb and flood periods in the port of Rotterdam area under a discharge of the Rhine at the Dutch-German border (Qbr) of 1000 $m^3 s^{-1}$.

The Rhine-Meuse estuary is microtidal, with an average tidal range of 1.75 m at Hoek van Holland, which gradually decreases upstream to 1.10 m at Hagestein on the Lek and 0.25 m at Heusden on the Meuse. At springtide, the tidal cycle at Hoek van Holland exhibits approximately a 4 h flood period, a 4 h ebb period of ebb and a 4.5 h low-water period.

Under conditions of average river discharge, the water above the sea floor of the harbours of the Nieuwe Maas (Fig. 2A) in the eastern region is fresh to oligohaline, but at discharges below 1000 $m^3 s^{-1}$, the area becomes α-mesohaline, with salinities over 10. When the discharge of the river Rhine remains below 1000 $m^3 s^{-1}$ for a few weeks during the shipworm breeding season, conditions might become favorable for this bivalve (Paalvast and Van der Velde, 2011). Larvae transported with the tidal currents to the eastern part of the port of Rotterdam area could settle and grow in the wooden oak and pine poles on which several old quays are build, in particular in harbours where the current velocity is considerably reduced. Salinity depth profiles show a sharp increase in salinity one to two metres above the sea floor at low river discharge (< 1000 $m^3 s^{-1}$), which makes this water layer suitable for settlement and growth of the shipworm. In the summer of 2003, the discharge of the river Rhine dropped to a level below 1000 $m^3 s^{-1}$, and the salinity in the eastern part of the port of Rotterdam area rose to levels above 10 (Paalvast and Van der Velde, 2011).

Risk analysis

SIMONA is the hydraulics information system for the Ministry of Transport (Ministry of Transport, Public Works and Water Management, 2008), consisting of a collection of mathematical simulation models that describes hydrodynamic processes. It includes four models for the simulation of hydrodynamic phenomena, such as simulations of tides, the transport of solutes in water, and water movement and it is designed as a layered system which makes use of uniform data storage. The port of Rotterdam Authority uses SIMONA for forecasting hydrodynamics 36 hours in advance twice a day.

Using the SIMONA modelling system with the (critical) river discharge (crit-Qbr) under the prevailing climate conditions in the eastern part of the port of Rotterdam as far upstream as the Rijnhaven (Fig. 2A), the salinity at one to two metres above the sea floor reaching a permanent level (9 or higher) corresponding to necessary conditions for the shipworm to settle and to grow, was computed (Fig. 3).

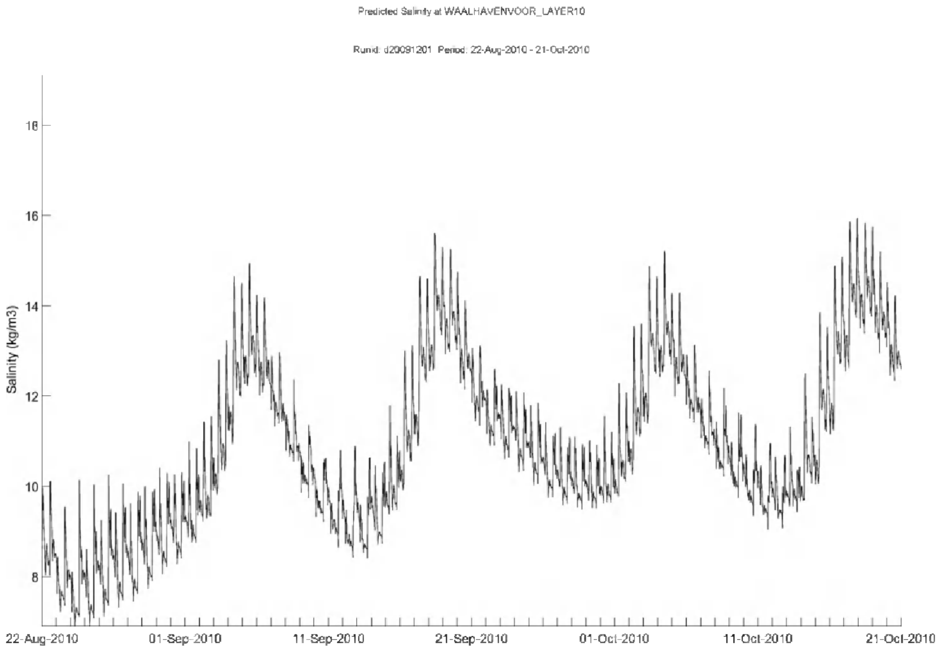

Figure 3. Example of the output of the SIMONA hydraulics knowledge system at a Qbr of 700 $m^3 s^{-1}$ for the salinity at the sea floor of the Waalhaven in the eastern part of the port of Rotterdam area.

Van den Hurk et al. (2006) of the Royal Netherlands Meteorological Institute have elaborated climate change scenarios for the Netherlands known as the KNMI'06 scenarios (Fig. 4). Two anticipated circulation regime changes are included in the scenarios: a strong circulation change, which induces warmer and moister winter seasons and increases the likelihood of dry, warm summer situations, and a weak circulation change. Both regimes are presented for the +1°C and +2°C global temperature increases for 2050 compared to 1990, producing a total of four scenarios. In the *G* scenarios the maximum mean sea level rise is 25 cm and in the *W* scenarios 35 cm.

Rhineflow (Van Deursen, 1995, 2003) is a spatially distributed water balance model of the Rhine basin that can simulate river flows, soil moisture, snow pack and groundwater storage with a 10 days time step. In order of the Ministry of Transport, Carthago Consultancy, Rotterdam, simulated the effects of these climate scenarios using this model in terms of percentage change (Fig. 5) in the daily river discharge (Van Deursen, 2006). This relative change in the discharge under each scenario was applied to measurements of the average daily discharge at the Dutch-German border (Qbr) over the period 1901-2008 to simulate the discharge under these scenarios. The crit-Qbr for the KNMI'06 scenarios in relation to sea level rise was elaborated.

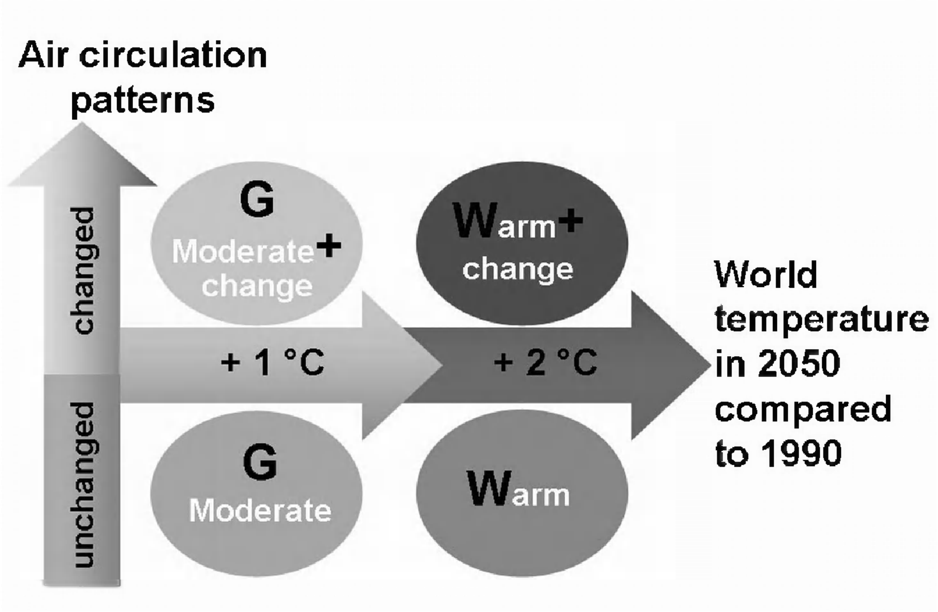

Figure 4. Schematic overview of the four KNMI'06 scenarios (after Van den Hurk, et al., 2006).

A period of 14 days of crit-Qbr was considered as the minimum for shipworm settlement and boring to cause damage, and a period of 42 days was considered for the shipworms to complete their life cycle (Richards et al., 1984). By counting the number of days per year on which the discharge over the period 1901-2008 and the simulated discharges over the same period for each of the KNMI'06 scenarios reached the crit-Qbr or lower, the number of periods of 14 days or longer and their repetition time (risk of damage) were calculated. The length of the periods was used to determine whether the shipworm could complete its life cycle in the eastern part of the port of Rotterdam under the KNMI'06 scenarios.

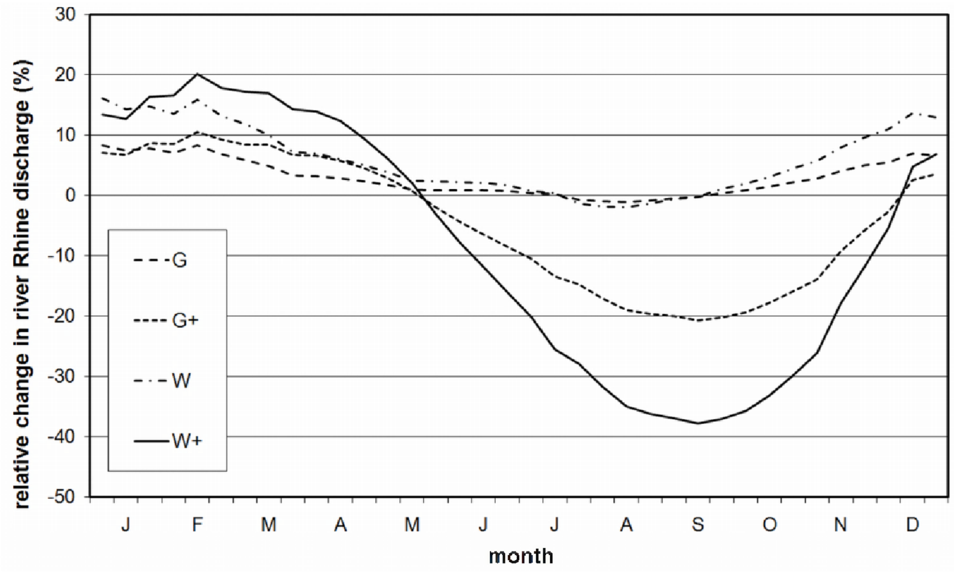

Figure 5. Simulated relative change in the discharge of the Rhine river as a consequence of the KNMI'06 scenarios (after Van Deursen, 2006).

Results

Risk of damage under the present conditions

Using the SIMONA modelling system it was calculated that for the port of Rotterdam area, a discharge of 700 $m^3 s^{-1}$ or less (crit-Qbr) of the Rhine river at the Dutch-German border under the prevailing climate conditions would lead, within a week to salinities of the bottom water in the harbours of the Nieuwe Maas in the eastern part of the port of Rotterdam upstream to the Rijnhaven (Fig. 2A) appropriate for settlement and growth of the shipworm (and thus expansion of its distribution upstream). From 1901 to 2008, the crit-Qbr was reached for a period of two weeks or longer in only three years (Table 1, Fig. 6), which indicates a repetition time of 36 years, or that the risk of damage is once in 36 years. The longest uninterrupted period lasted 34 days, which is too short for the shipworm to complete its life cycle.

Table 1. Number of years with periods of 14 days or longer with a crit-Qbr or lower and years with a Qbr < 600 $m^3 s^{-1}$ with a risk of shipworm damage under the present climate conditions (1990) and the KNMI'06 scenarios for 2050, the length of the periods, their repetition time and the number of periods > 42 days for the shipworm to complete its life cycle.

climate scenarios	present	G	G+	W	W+
number of years	3	5	18	4	45
number of extreme years Qbr < 600 $m^3 s^{-1}$	0	0	3	0	11
number of periods	3	7	20	4	46
average length periods in days	21.7	25.1	53.7	52.0	57.0
standard deviation	10.7	11.6	34.5	31.3	33.6
maximum length in days	34.0	49.0	132.0	93.0	142.0
minimum length in days	15.0	16.0	14.0	27.0	14.0
median length in days	16.0	19.0	46.0	44.0	49.5
repetition time in years	36	21.6	6	27	2.4
number of periods > 42 days	0	1	10	2	26

Risk of damage due to climate change

With the sea level rise under the KNMI'06 scenarios for 2050, the required salinity conditions for the settlement and growth of the shipworm in the eastern part of the port of Rotterdam upstream to the Rijnhaven (and, thus, expansion of its distribution upstream) will occur at a discharge of approximately 800 $m^3 s^{-1}$ or lower (crit-Qbr).

Under the scenarios *G* and *W*, with a weak change in air circulation patterns, there is only a slight decrease in river discharge in summer and fall (Fig. 5), and thus the increase in number of days with a crit-Qbr is small compared with the number of days with a crit-Qbr observed over the period 1901-2008 (Fig. 6- 8). For the *G* and *W* scenarios, the crit-Qbr is reached for 14 days or longer in only 5 and 4 years, respectively, resulting in a risk of damage once in 22 and 27 years (Table 1). Under both scenarios, the shipworm is able to complete its life cycle in 1 and 2 years over a period of 108 years for *G* and *W*, respectively.

Under a future climate with a strong change in air circulation patterns, scenario *G+* leads to many days and to several periods of 14 days or longer associated with a crit-Qbr in summer and fall (Table 1, Fig. 7 and 8) and a considerable risk of damage once in 6 years. In 50% of these periods, the shipworm is able to complete its life cycle between one to three times in a year. In three periods the crit-Qbr reaches values less than 600 $m^3 s^{-1}$ for several days.

Under a future climate with a strong change in air circulation patterns, scenario *W+*, will bring a period of 14 days or longer with crit-Qbr almost once in approximately 2 years, and once in 4 years, the shipworm could complete its life cycle from one to three times in a year.

Under the *G+* and *W+* scenarios, there is no significant difference in the lengths of periods of potential shipworm damage (t(64)=-0.37, p>0.7).

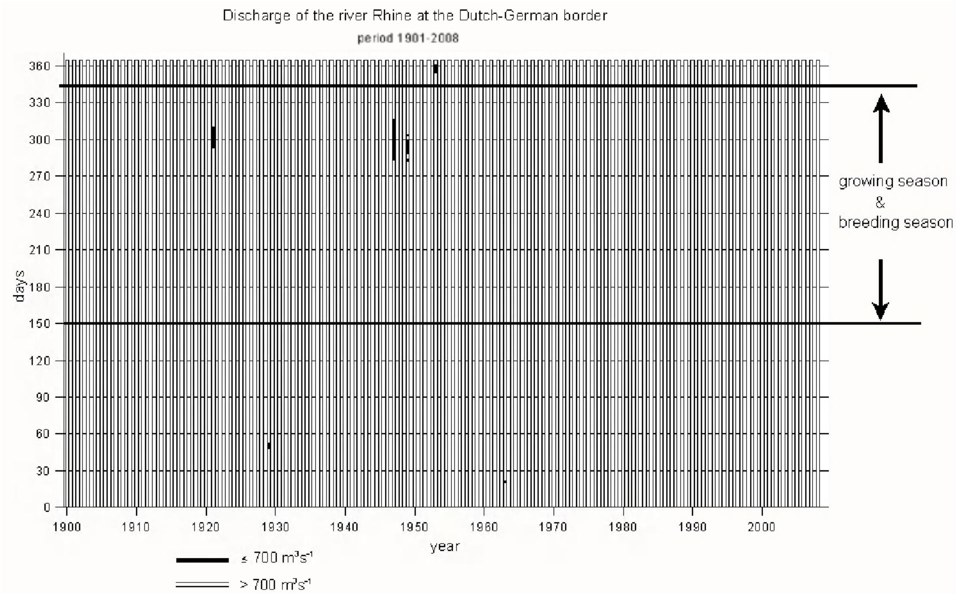

Figure 6. Periods of discharges of the river Rhine at the Dutch-German border of ≤ 700 $m^3 s^{-1}$ during the period 1901- 2008 and their occurrence in the breeding and growing season of the shipworm.

Discussion

The increased risk of the expansion of the shipworm towards the eastern part of the port of Rotterdam as far as the Rijnhaven depends greatly on a temperature increase with changed air circulation patterns. However, under the present situation, at discharges below 1000 $m^3 s^{-1}$, there is a salinisation above the sea floor in the most downstream part of the eastern portion of the port of Rotterdam that creates conditions for the shipworm to settle and grow. Paalvast and Van der Velde (2011) demonstrated that with the flood stream, shipworm larvae could travel 20 km stream upwards to 0.5 km before the confluence of the Nieuwe Maas and Oude Maas during a period in which the discharge of the Rhine was slightly higher than 1000 m^3 s^{-1}. Under the *G* and *W* scenarios the probability of shipworm attacks in the eastern part of the port of Rotterdam increases slightly compared with the present situation, but the periods with critical discharges are becoming much longer, so the eventual damage to wooden constructions will also increase.

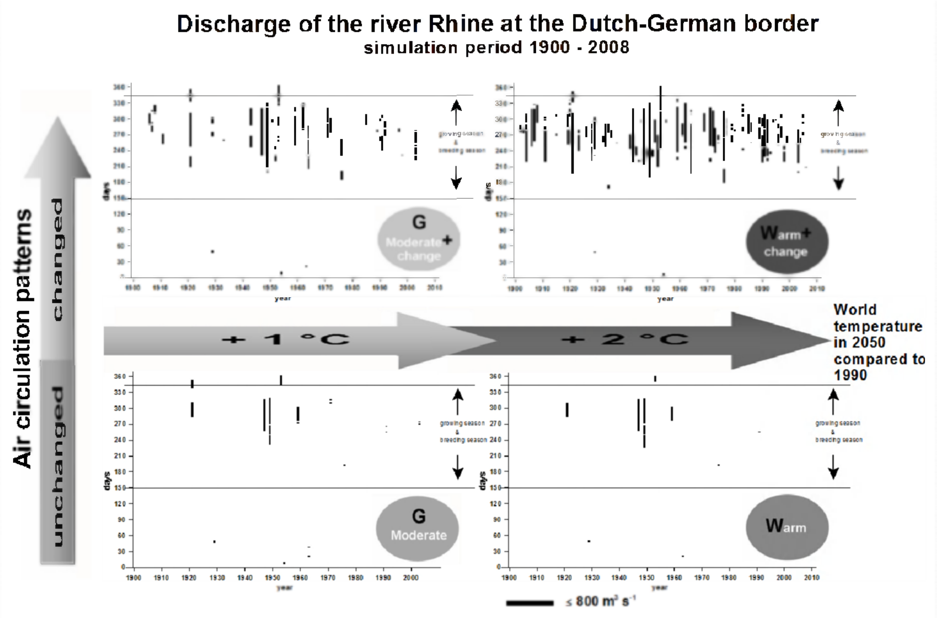

Figure 7. Simulated periods of discharges of the Rhine river at the Dutch-German border of ≤ 800 m^3 s^{-1} during the period 1901- 2008 and their occurrence in the breeding and growing season of the shipworm as a consequence of the KNMI'06 scenarios.

Under the *G+* and *W+* scenarios, the probability of the risk of shipworm attacks and damage of underwater fir and oak harbour structures in the eastern part of the port of Rotterdam greatly increases, not only due to a decrease in repetition time, but also because the periods with a crit-Qbr or lower persist over 2 months on average, which is long enough for the shipworm to reach maturity and to reproduce.

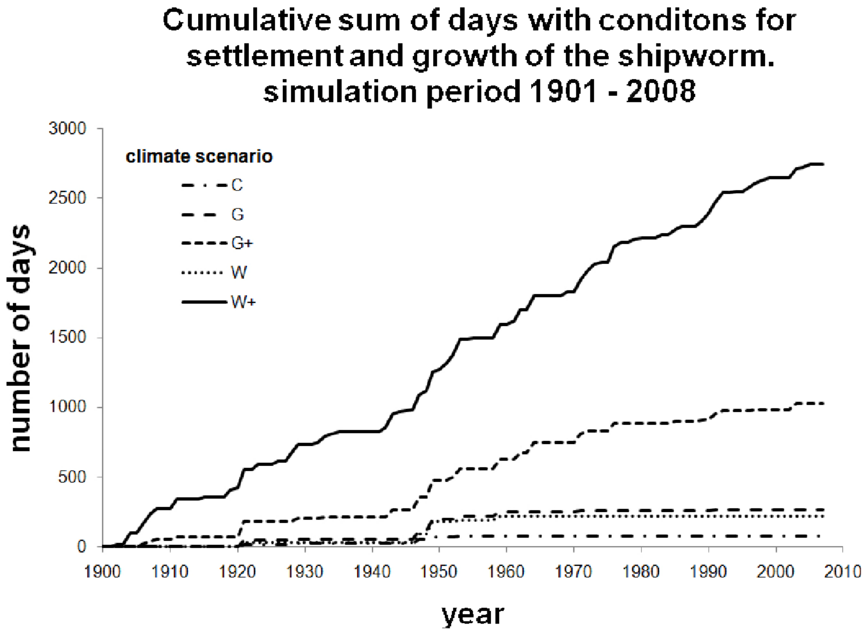

Figure 8. Cumulative sum of events with potential shipworm damage in the eastern part of the Port of Rotterdam under the prevailing climate conditions (*C*) and the KNMI'06 scenarios as simulated for the period 1901 – 2008.

Once settled, these animals are able to continue to grow and thus causing damage, even with a discharge of exceeding the crit-Qbr by 200 $m^3 s^{-1}$. When the salinity drops below 9 during the ebb phase, shipworms close their boring tubes using their pallets and reopen them when the salinity conditions become favourable again under flood conditions. If the salinity during both ebb and flood periods remains too low, the animals will survive for 6 weeks before they die.
Under the *G+* and *W+* scenarios, there are years presenting extreme salinisation of the eastern part of the port of Rotterdam due to long periods of Qbr approximately 600 $m^3 s^{-1}$, due to which the oldest harbours of Rotterdam, approximately 1 km upstream from the Rijnhaven, become at risk, which may possibly also affect the historic ships at the quays.
The shipworm will not be able to settle permanently in the eastern part of the port of Rotterdam due to large winter and spring discharges that occur at present, and even greater discharges due to climate changes will wash out the brackish water from the harbours for a few months, which is a period much too long for the shipworm to survive.

In addition to the eastern part of the port of Rotterdam, in the shallower old harbours of Maassluis and Vlaardingen, the conditions might become favourable under the scenarios *G+* and *W+* for the shipworm to settle and grow in the fir piles on which the old quays are built, and if they are not replaced by that time, the mechanical stability of the piles and, consequently, that of the quays will be impaired.

Paalvast and Van der Velde (2011) found an average body length growth rate of 1.5 mm day^{-1} in 2006 and wood consumption of 12.4% of fir wood panels in the polyhaline harbours in the western part of the port of Rotterdam by first year shipworm individuals in 130 days. The number of shipworm attacks per m^2 accounted approximately 250. Hoppe (2002) recorded 40,000 larvae per m^2 on wood after one month of exposure. These figures clearly show the potential threat of the species, and therefore, it is not surprising that when shipworms encounter structures made of wood into which they can bore, these are ruined in a short period of time. The complete destruction of a U.S. Navy base in the San Francisco Bay from 1919-1920 serves as a good example of the destructive capabilities of these bivalves (Cohen, 2004). However, not only climate change, but also the improvement of water quality will have an effect on the distribution of the shipworm in estuaries. After the Clean Water Act of 1972, pilings that stood in the Hudson estuary in New York, USA for 100 years began to fall, and more recently, parts of the wooden Brooklyn pier collapsed due to shipworm damage. The city of New York has already spent hundreds of millions of dollars fixing wooden support pilings (Cobb, 2002). Additionally, in the Rotterdam port area, the water and sediment quality has been improved since the 1970's, when pollution was severe. This was due to the decreasing levels of pollutants in the Rhine river as a result of the Rhine Action Plan following the Sandoz accident in 1986 (Admiraal et al., 1993, Bij de Vaate et al., 2006).

Various types of tropical timber (hardwood) have been tested over a period of 30 years in the marine waters of the Netherlands (Koninklijk Instituut voor de Tropen, 1972). The results showed that not only the hardness of timber, but also the presence of silica particles and poisonous alkaloids in wood affords considerable protection against shipworm attacks. However, even the most resistant hardwoods showed at least some damage by the shipworm after 30 years of exposure. The shipworm lives in the outer 3 cm of hundreds of pilings, fender structures and piers made of the hardwood basralokus (*Dicorynia paraensis* Benth.) and in driftwood in the polyhaline harbours of the port of Rotterdam (Paalvast and Van der Velde, 2011). With a reproductive rate of up to 2 million larvae per individual (Hoppe, 2002) and the ability to travel over large distances through the flood stream, this species is on standby to attack wooden structures upstream once the river discharge decreases and salinity rises.

Furthermore, the increased length of the salinity gradient and, consequently the expansion of the distribution of the shipworm upstream that are predicted within the Rhine-Meuse estuary as a consequence of climate change due to global warming will be similarly manifest in other northwest European estuaries, like the Elbe, Thames and Loire. The impact of climate change in Southern Europe estuaries will be even stronger under the worst case scenario, *W+* as in summer and fall, the decrease in precipitation may reach as much as 80% (Van den Hurk et al., 2006). When salinity rises to levels favourable for the shipworm to settle and grow in places where wooden constructions are located in southern estuaries, these constructions will eventually be attacked by the animal and will be seriously impaired or may collapse.

This study on the effects of global warming due to climate change on the expansion of the distribution of the shipworm upstream in the Rhine-Meuse estuary clearly shows how ecologists can benefit from computer models developed by meteorologists and hydrologists. Despite the limitations and uncertainties that each model has, they are invaluable in providing insight into the ecological impacts of climate change.

Conclusion

Climate change with a global increase in temperature of one or two degrees coinciding with a strong change of air circulation that leads to low river discharges in summer and fall will extend the salinity gradient upstream in western Europe estuaries and considerably increase the risk of damage to wooden structures by the shipworm in the near future.

Acknowledgements

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