Ecological studies in a man-made estuarine environment, the port of Rotterdam

Peter Paalvast

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Though all the fates

Though all the fates should prove unkind,
Leave not your native land behind.
The ship, becalmed, at length stands still;
The steed must rest beneath the hill;
But swiftly still our fortunes pace
To find us out in every place.

The vessel, though her masts be firm,
Beneath her copper bears a worm;
Around the cape, across the line,
Till fields of ice her course confine;
It matters not how smooth the breeze,
How shallow or how deep the seas,
Whether she bears Manilla twine,
Or in her hold Madeira wine,
Or China teas, or Spanish hides,
In port or quarantine she rides;
Far from New England's blustering shore,
New England's worm her hulk shall bore,
And sink her in the Indian seas,
Twine, wine, and hides, and China teas.

Henry David Thoreau (1817-1862)

To my grandsons Tom Pieter, Noah (†) and Daniël.

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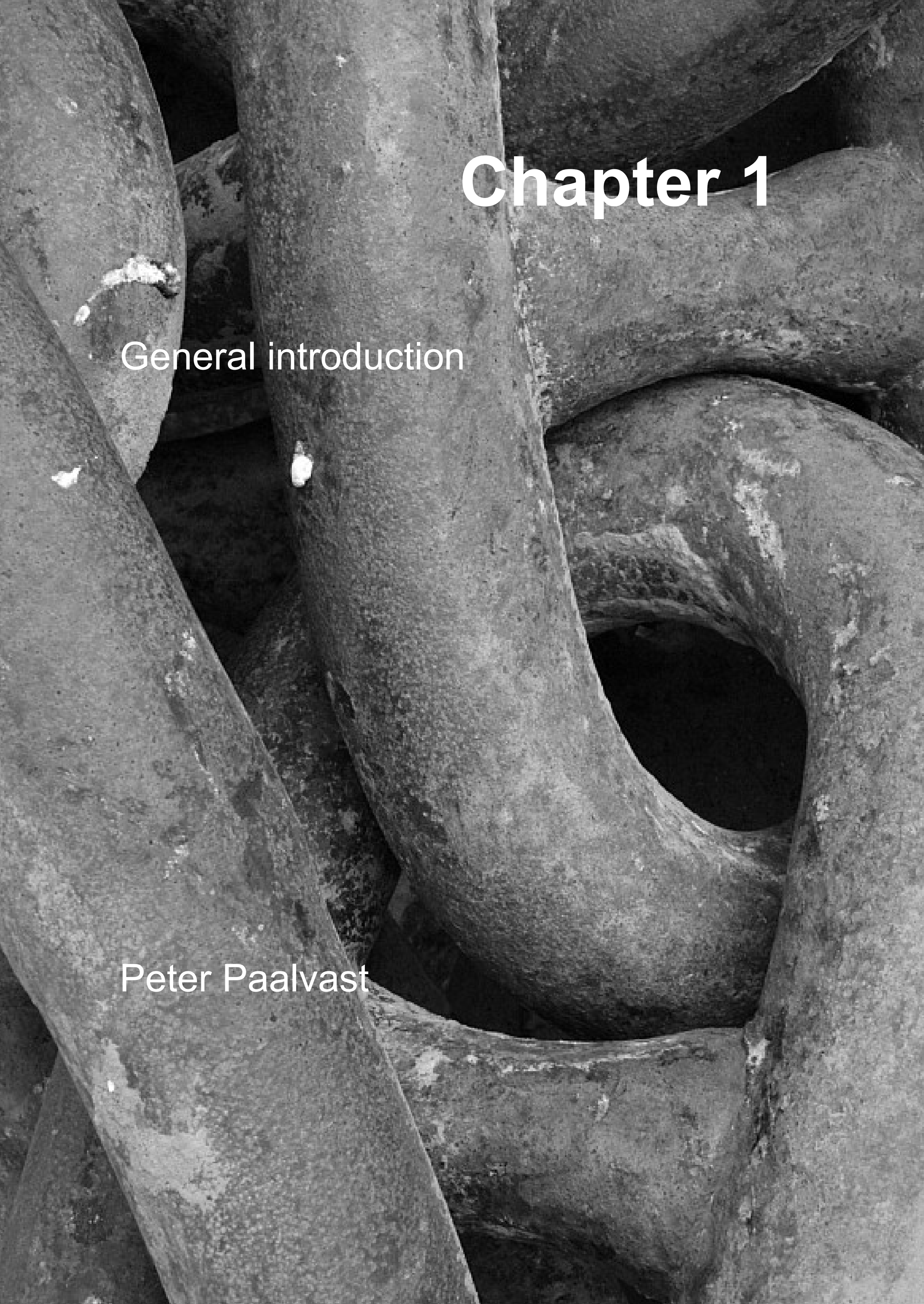

Chapter 1

General introduction

Peter Paalvast

The port of Rotterdam is located in the so-called "Noordrand" of the northern delta basin of the Netherlands (Fig. 1). It comprises the Nieuwe Maas and Nieuwe Waterweg (including Scheur) with adjacent harbour systems and a part of the Oude Maas.
Rotterdam received its city rights from Count William IV on June 7, 1340. In the beginning of the second half of the 14th century, newly constructed canals (Coolse and Goudse vest) that served as a defence line around the city came in use as harbours (Brolsma, 2006). Well into the 17th century Rotterdam was mainly a herring port leading to related economic activities to conserve the herring for trade. The Rhine hinterland was a major customer, but also Rouen in northern France was an important destination for herring products. On the return trip a range of goods was carried and Rotterdam developed itself more and more as a transhipment port. The growth of the port kept pace with the economic development of Holland and from the mid-19th century with that in the German Rhine and Ruhr area.

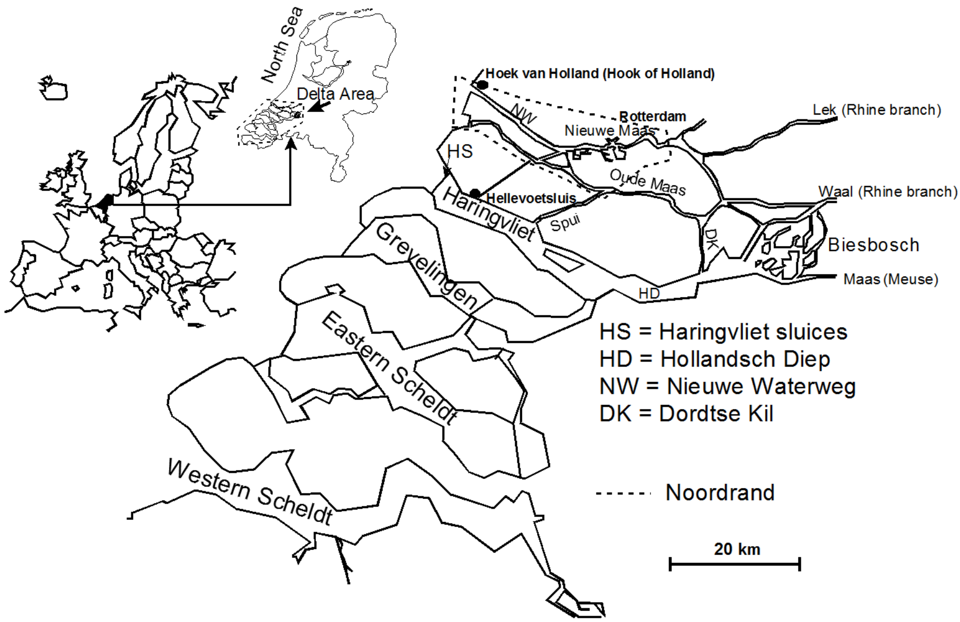

Figure 1 The location of the port of Rotterdam area at the Noordrand in the northern part of the Delta Area in the Netherlands.

Large harbour expansions took place in particular in three periods: a) so-called Golden Age of the Netherlands (1600-1700), b) the industrial revolution in the mid 19th century and c) after the second World War (WWII) (1945-nowadays) in particular. In the period 1962-2004, the port of Rotterdam in terms of cargo handling could call itself the largest port of the world. Nowadays, Rotterdam is the fifth largest port in the world behind ports such as Shanghai (China) and Singapore, but by far the largest of Western Europe.

Hydrology and salinity

Human interference in the area by land reclamation and port development have had an enormous impact on the hydrology of the area (see Table 1), which is reflected in changes in the average yearly tidal range (difference between low and high water level), water velocities, sediment transport and salt intrusion. But also the global sea level rise of about 21 cm between 1880 and 2009 (Church and White, 2011) must have had an important influence on the hydrology. At Hoek van Holland the sea level rise between 1890 and 2008 was even higher, viz. 30 cm (Fig. 2)(Dilling et al., 2012).

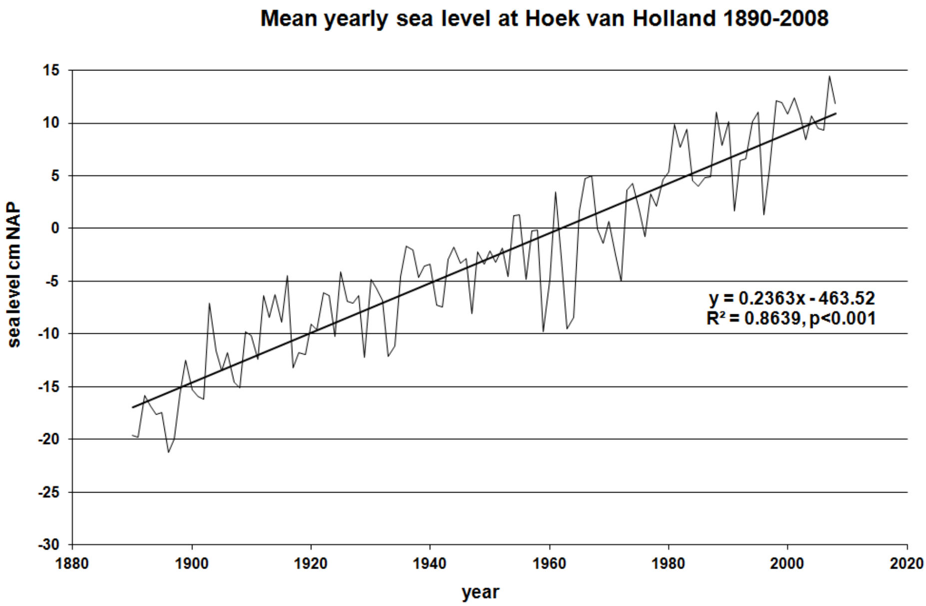

Figure 2 Changes in mean yearly sea level at Hoek van Holland (Hook of Holland) between 1890 and 2008 (redrawn after data from Dilling et al., 2012). NAP=Amsterdam Ordnance Datum.

Water levels in the area were first recorded at Brielle (Fig. 3) at 1815 and were continued (with missing data from 1818, 1820 and 1822) till the closure of the Brielsche Maas in 1950 (data till 1949). Between 1830 and 1870 based on 10 year averages there is a decrease in tidal range from 163 cm till 140 cm (Fig. 4). The cause of it was the natural silting up of the mouth of the Brielsche Maas.

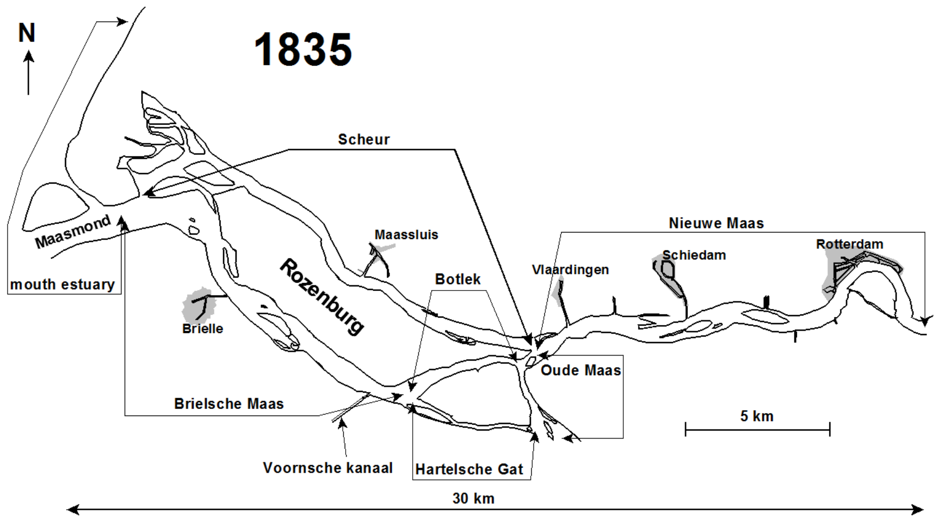

Figure 3 Topography of the "Noordrand" in 1835. Drawn after old river maps.

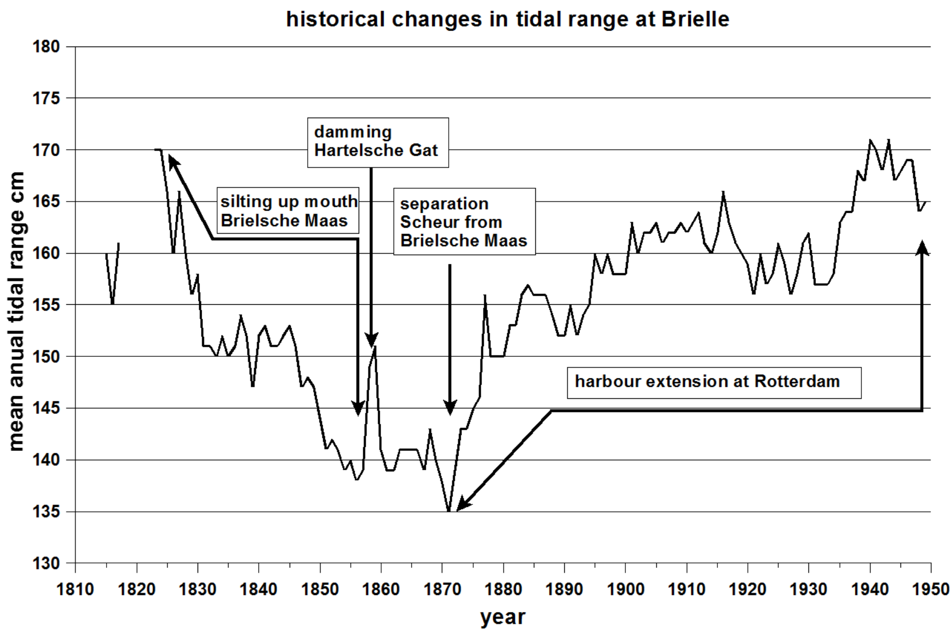

Figure 4 Historical changes in tidal range at Brielle at the Brielsche Maas between 1815 and 1950 (after data provided by Rijkswaterstaat).

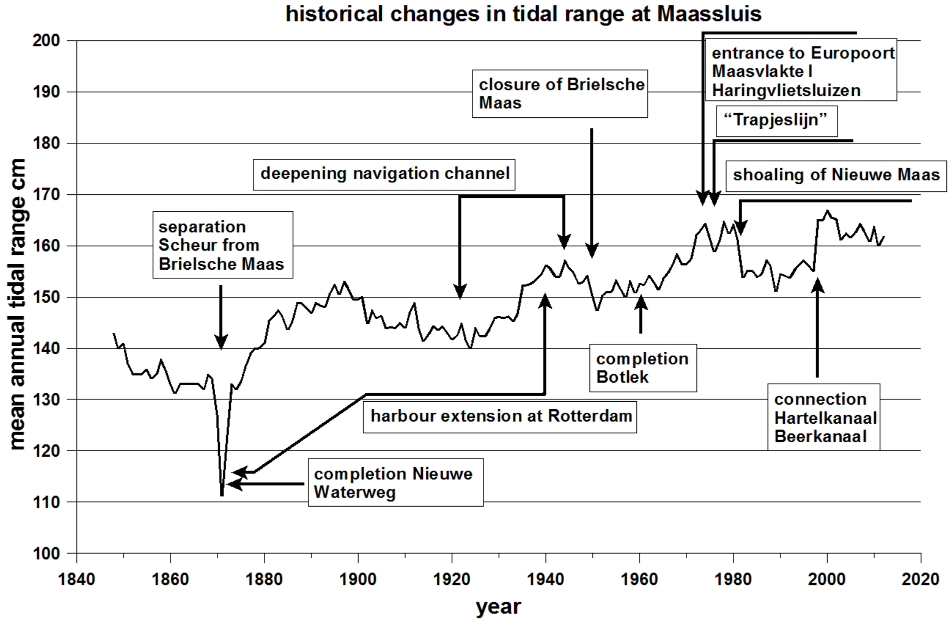

Figure 5 Historical changes in tidal range at Maassluis at the Scheur between 1850 and 2010 (after data provided by Rijkswaterstaat).

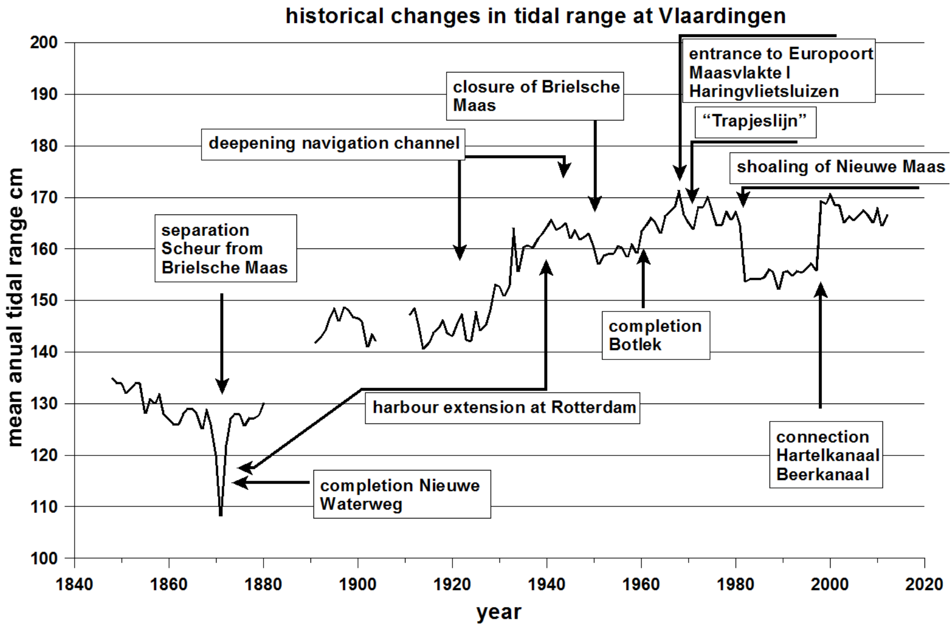

Figure 6 Historical changes in tidal range at Vlaardingen at the Scheur between 1850 and 2010 (after data provided by Rijkswaterstaat).

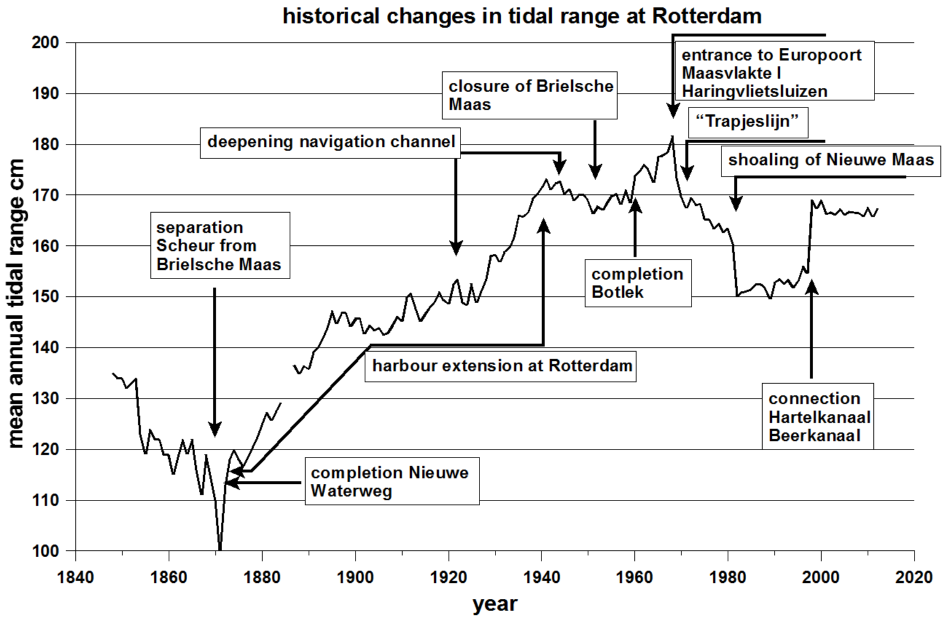

Figure 7 Historical changes in tidal range at Rotterdam at the Nieuwe Maas between 1850 and 2010 (after data provided by Rijkswaterstaat).

The cause of the increase in the average yearly tidal range at Brielle in 1858 and 1859 seems unclear but might be the effect of the damming of the Hartelsche Gat in 1857 (Fig. 4).

The recording of the water levels at Maassluis, Vlaardingen and Rotterdam started all around 1850. The graphs in figure 5, 6 and 7 all show a decrease in tidal range due to sedimentation in both Scheur and Nieuwe Maas before 1868. In 1868 the excavation of the Nieuwe Waterweg through the dunes of Hoek van Holland started and the canal was opened in 1872. The connection between the Brielsche Maas and the Scheur became closed in 1872. To separate the Scheur from the Brielsche Maas first the banks were reinforced and in 1871 a low water dam was constructed. The effect of this low water dam is clearly shown in figures 5, 6 and 7 by a decrease in the average yearly tidal range of 1871 for Maassluis, Vlaardingen and Rotterdam compared with 1870 of 16 cm, 12 cm and 10 cm, respectively. At Brielle this was less clear as this difference in tidal range between 1871 and 1870 was only – 3 cm.

After the completion of the Nieuwe Waterweg the port water surface quadrupled from 50 to 200 ha between 1872 and 1900 (see chapter 2). Also the average wet cross section of the river increased by dredging for greater depth and widening of the mouth of the Nieuwe Waterweg (Table 1). These interventions led to a considerable increase in channel detention of this part of the estuary and resulted in a rise in tidal range of 20 cm at Maassluis and Vlaardingen and

Table 1 Historical morphological and hydrological changes in the Nieuwe Waterweg and Scheur (after Van Os, 1993).

year	1874	1908	1956	1963	1971
average width m	141	375	375	410	410
average depth m	7.7	7	10.8	11.8	15.8
wet cross section m^2	1089	2626	4048	4846	6478
river discharge $m^3 s^{-1}$	358	649	738	895	1550
flood volume $10^6 m^3$	25	47	69	83	94
maximum ebb velocity $m s^{-1}$	1.61	1.24	1.2	1.21	1.02

about 30 cm at Rotterdam (Fig. 5 to 7). The period 1897 till 1909 is considered as the first period in which sedimentation and erosion of the Nieuwe Waterweg were in equilibrium with each other (Haring, 1977) and no significant increase in tidal range occurred. Within the period of 1910 till 1923 many harbours were constructed or under construction, for example the Waalhaven (261 ha), by which the flood volume strongly increased and by dredging and possible erosion of the Brielsche Maas, Scheur and Nieuwe Waterweg the tidal range as a consequence of this further increased. Between 1924 and 1944 from the mouth of the Nieuwe Waterweg to 1 km upstream Rotterdam the whole river was deepened increasing the flood volume and tidal range stream upwards again. On the contrary the tidal range at Hoek van Holland probably due to sedimentation near the mouth dropped between 1910 and 1950 about 10 cm. In 1950 the Brielsche Maas was dammed leading to an approximately 20% increase in river water discharge via the Nieuwe Waterweg (Haring, 1977), a situation that remained unchanged until the closure of the Haringvliet in 1970 as part of the Delta Project (see chapter 2). With the closure of the Haringvliet and the management of the Haringvliet sluices the discharge of river water via the Nieuwe Waterweg at an average river discharge of 2200 m^3/s at the Dutch German border increased from 950 m^3/s to 1700 m^3/s (Paalvast et al., 1998). Also the construction of weirs that close at low river discharges in the Lek (and Nederrijn) as part of the Rhine channelization programme affected the tidal range. The period 1950-1958 is considered as the second equilibrium of sedimentation and erosion and no change in tidal range took place. Between 1958 and 1964 many improvement works for shipping such as dredging for greater depth for the new harbour systems Botlek and Europoort were carried out leading to an increase of 10 cm in tidal range at Rotterdam. The decline in tidal range at Rotterdam and rise of tidal range in particular at Hoek van Holland in 1971 (Fig. 6) were the result of the enormous increase of the channel detention by opening of the Beer- and Calandkanaal harbour system. The construction of the large harbour systems and the deepening of the navigation channel had a great impact on the salt intrusion upstream and consequences for both the intake of drinking water and the supply of water for agriculture. To reduce this salt intrusion the water depth of the Nieuwe Waterweg (and Scheur) and Nieuwe Maas was managed by either dredging from or supplementation of sediment (Nieuwe Maas and parts of the Nieuwe Waterweg) on the river bottom in a stepwise way from mouth to upstream as far as Rkm 955 from respectively -22.5 metres relative to NAP and -8.0 metres relative to NAP (Fig. 8). This stepwise intervention in the river bottom is called “Trapjeslijn” in Dutch and the works started in 1968 and were finished in 1972 reducing the tidal range by a few cm’s. In fact the “Trapjeslijn” is a compromise between the need to reduce the salt intrusion, which requires a water depth reduction, and the need of greater depth for navigation. In the first years the “Trapjeslijn” was well maintained, but later on shipping prevailed and in particular the depth of the Nieuwe Waterweg and the route to the Waalhaven at the Nieuwe Maas

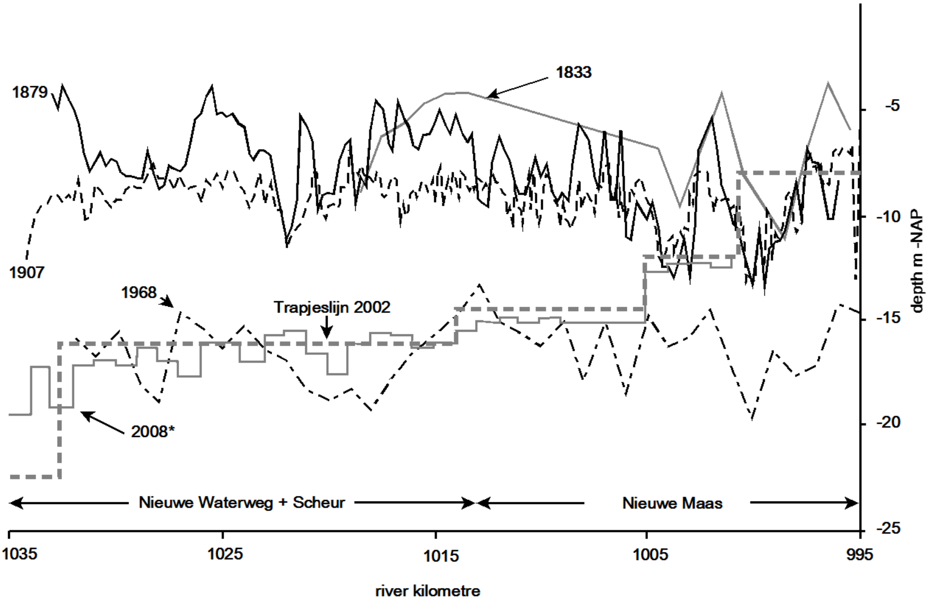

Figure 8 Historical changes in the depth of the navigation channel of Nieuwe Waterweg, Scheur and Nieuwe Maas. The depths of 1833, 1879 and 1907 were retrieved from old river maps, those of 1968 from data of Deltares. Trapjeslijn 2002 = design of river bed elevation 2002. 2008 = average depth of the navigation channel per river kilometre (redrawn from Kuijper and Kaaij, 2009). NAP= Amsterdam Ordnance Datum.

increased again (Rijkswaterstaat, 2004). The deliberate shoaling of the Nieuwe Maas in 1984 decreased the tidal range at Rotterdam by another 10 cm (Fig. 7). In December 1997 the Beerkanaal was connected with the Hartelkanaal (see Fig. 11) which led to a new rise in tidal range at Maassluis, Vlaardingen and Rotterdam of 10 cm, 13 cm and 14 cm, respectively. Since then the tidal range remained similar.

The historical change in tidal range along the Nieuwe Maas, Nieuwe Waterweg and Brielsche Maas is significantly correlated with the increase of the port water surface or harbour extension (in fact all the deepening and widening of the waterways to the harbours).This is clearly shown in the graphs for Brielle (Fig. 9) and Rotterdam (Fig. 10). The weaker correlation for Brielle (Fig. 9), Maassluis ($Y=3.86\ln(X)+125.12$, $R^2=0.48$, $p<0.001$) and Vlaardingen ($Y=10.71\ln(X)+86.75$, $R^2=0.86$, $p<0.001$) compared with Rotterdam (Fig. 10) is related to their shorter distance from the sea. If the extension of the port surface by the creation of Europoort and Maasvlakte 1, that led to an increase of the channel detention at the mouth, is disregarded then correlation between harbour extension and increase in tidal range at Rotterdam is even stronger ($R^2=0.913$ vs $R^2=0.906$, figures not round off).

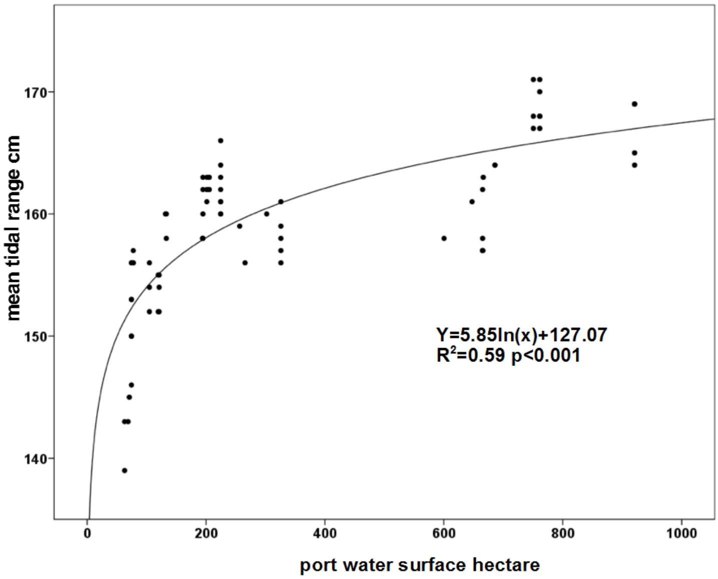

Figure 9 Relation between harbour extension along the Nieuwe Maas near Rotterdam and the mean tidal range at Brielle between 1872 and 1949.

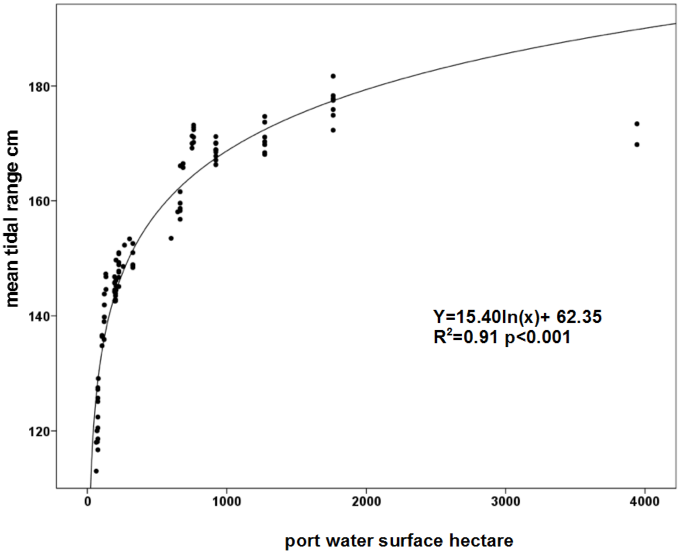

Figure 10 Relation between harbour extension along the Nieuwe Maas near Rotterdam and the mean tidal range at Rotterdam between 1872 and 1970.

There are not many historical salinity data of the Rotterdam port area as monitoring started in the 1970s when the Haringvlietsluizen came into operation. In the months of September 1907 and July 1908 however salinity measurements were carried out in the northern part of the Dutch delta area by Rijkswaterstaat. On the basis of the minimum and maximum values that were acquired isohalines for the average river flow in those months were derived (Fig. 11). Peelen (1967) calculated the isohalines of the Delta area for the period (1960-1970) before the closure of the Haringvliet, Grevelingen and Oosterschelde. The underlying data were used by Wolff (1973) to calculate the salinity at the bottom of the rivers and the sea floor (Fig. 12). They clearly show the effect of deepening of the navigation channel on salt intrusion, which was more stream upwards in the period 1960-1970 than it was in 1907 and 1908 (Fig. 12). Around 1970 Beer- and Calandkanaal were connected to the sea and the Nieuwe Waterweg and in this way a large polyhaline area was formed. In that same year the management scheme of the Haringvliet sluices was implemented and extra river water from then on is forced through the Noordrand to reduce salt intrusion. The reduction of salt intrusion by means of the management of the Haringvliet sluices and the “Trapjeslijn” becomes clear by comparing the isohalines of around the year 2000 (Fig. 13A) and those of the period 1960-1970 (Fig. 12A).

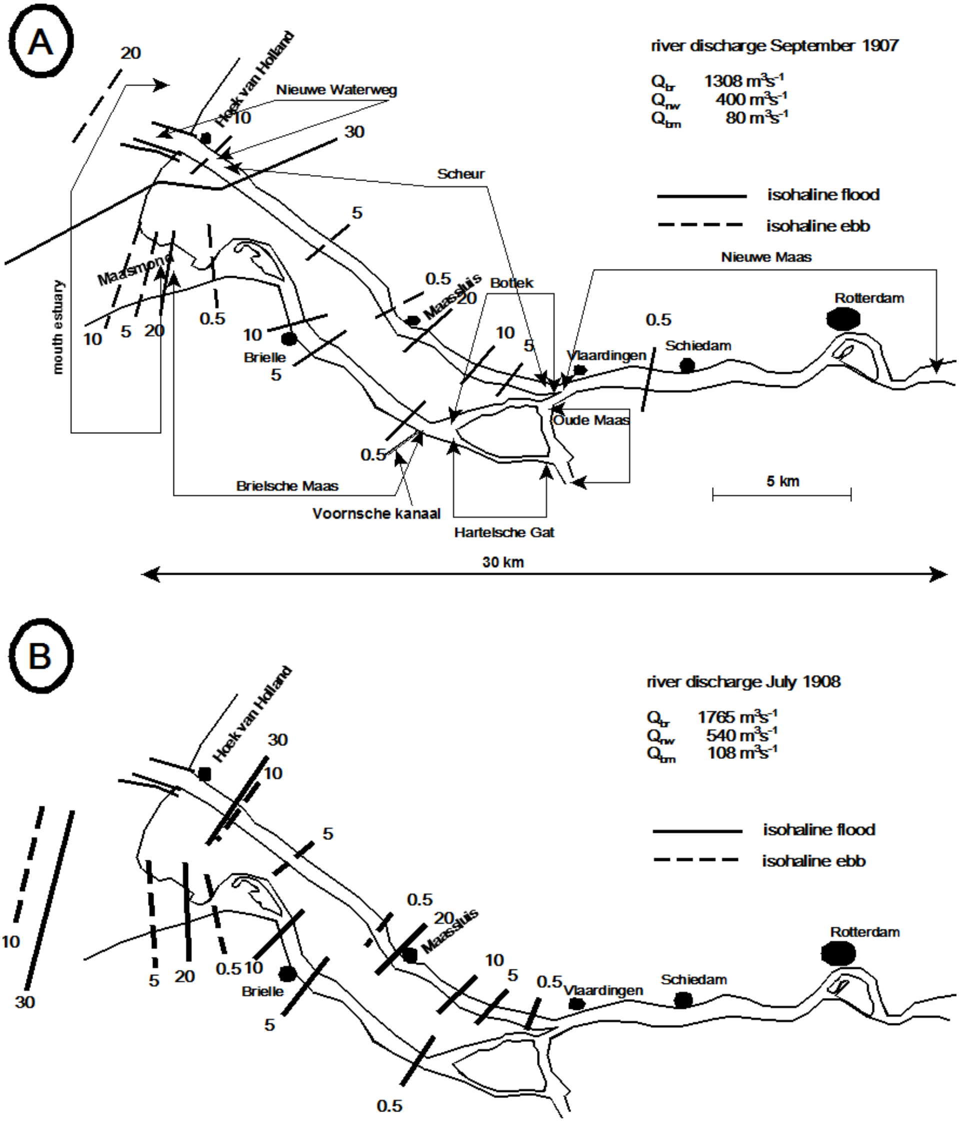

Figure 11 Isohalines (S) at the bottom in the Noordrand in September 1907 (A) and July 1908 (B) (after data from Anonymus, 1911).Q_{br} = monthly average discharge at the Dutch-German border, Q_{nw}= monthly average discharge Nieuwe Waterweg, Q_{bm}= monthly average discharge Brielsche Maas.

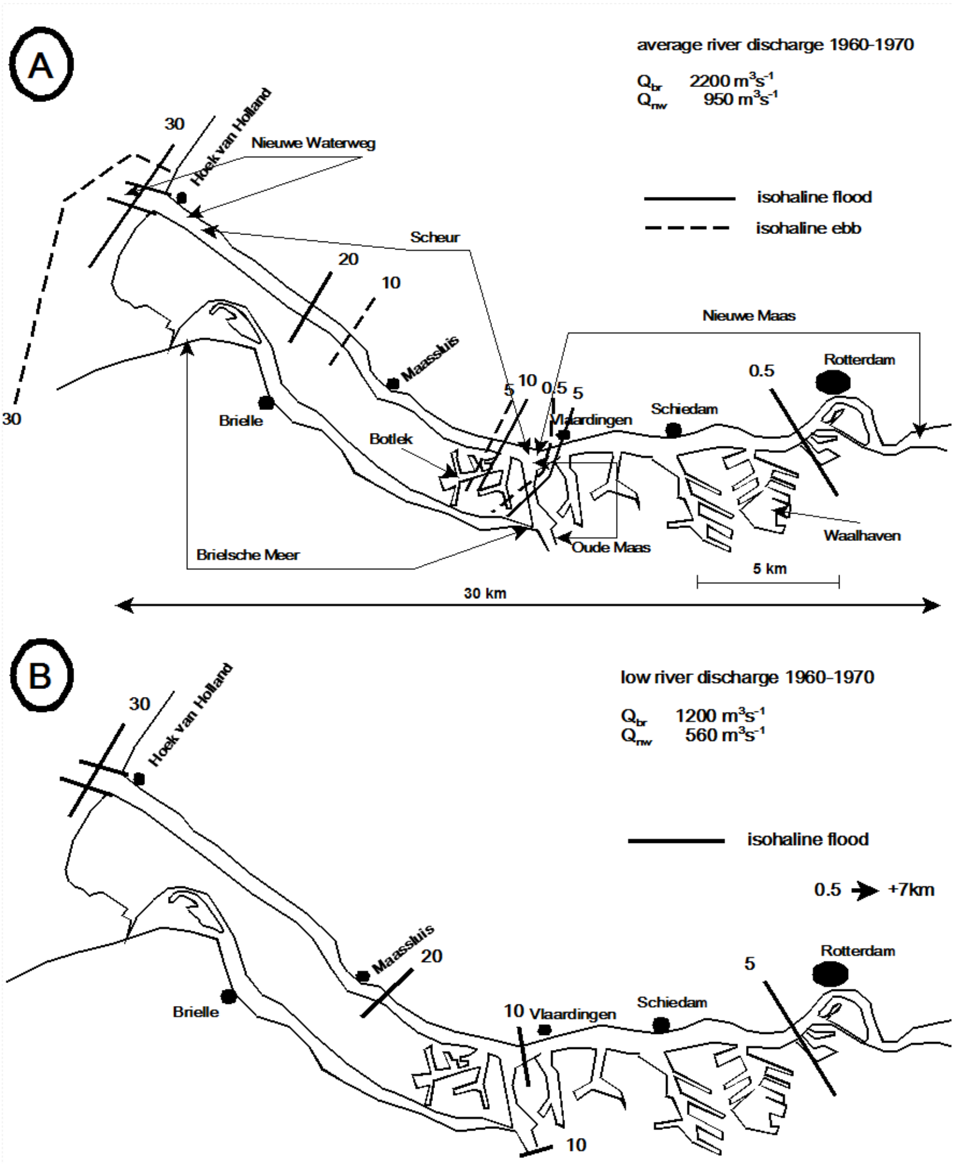

Figure 12 Isohalines (S) at the bottom in the Noordrand in between 1960 and 1970 (redrawn after Wolff, 1973). A. at average discharge at the Dutch German border. B. at low discharge at the Dutch German border. Q_{br} = discharge at the Dutch-German border, Q_{nw}= discharge Nieuwe Waterweg.

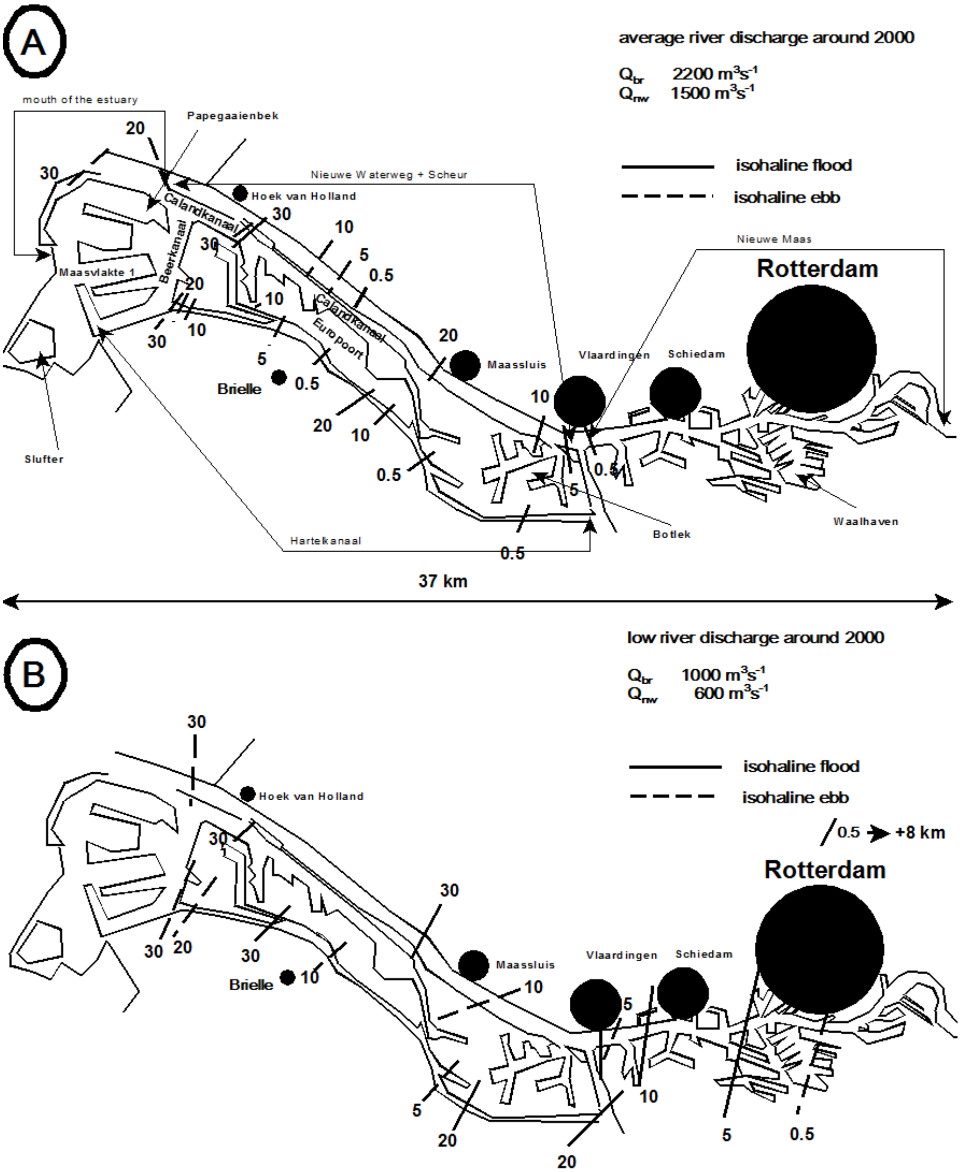

Figure 13 Isohalines (S) at the bottom in the Noordrand in around 2000 calculated with the model RIJMAMO 3D (Bol and Kraak, 1998). A. at average discharge at the Dutch German border. B. at low discharge at the Dutch German border. Q_{br} = discharge at the Dutch-German border, Q_{nw}= discharge Nieuwe Waterweg.

Ecological monitoring

The pollution of water and soil in the period after WWII, especially in the 1960s and 1970s was the major reason for the neglectance of ecological studies in the Noordrand (Den Hartog, 1963a, Wolff, 1973, Heerebout, 1974). During that period the port of Rotterdam area was considered as almost biologically dead. There are a few exceptions. For example before and after the closure of the inlets of the delta region inventories of higher plants along the banks have been taken place by members of the KNNV (the Royal Dutch Society for Natural History) and employees of the DIHO (Delta Institute for Hydrobiological Research). The data gathered are included in the Atlas of the Dutch Flora (FLORON, 2012). Den Hartog (1959) and Nienhuis (1974) have paid attention to the algae of the littoral zone of the area. Further Den Hartog (1963b, 1964) investigated the amphipods in the Delta region and found the talitrid amphipods *Orchestia cavimana* and *O. gammarella* along the Nieuwe Waterweg and Nieuwe Maas but no gammarid amphipods. Gammarids were only found on the piers in the mouth of the Nieuwe Waterweg. Further fauna records are anecdotal for example the first observation of the Chinese mitten crab (*Eriocheir sinensis*) in the harbours Rotterdam and the mouth of the Nieuwe Waterweg in 1931 (Kamps, 1937), the Brackish water mussel *Mytilopsis leucophaeata* (syn. *Congeria cochleata*) in the harbour of Maassluis in 1946 (pers. comm. Wim Kuijper) or the Dog whelk (*Nucella lapillus*) on the northern pier at Hoek van Holland (Smits, 1954). No studies were carried out in the Nieuwe Waterweg, Scheur or Nieuwe Maas. Only on a few occasions the hard substrate of the pier of Hoek van Holland at the mouth of the Nieuwe Waterweg was investigated (Wolff, 1968). In the years after the large inlets (Oosterschelde, Grevelingen and Haringvliet) as part of the Delta project were closed more floristic and faunistic research in the Noordrand has been conducted in particular in the context of the monitoring of the chemical and ecological condition of the Dutch water bodies (MWTL) (Boogaart-Scholte et al., 2012). Within the Noordrand there are a small number of measuring points but the harbours were excluded, in spite of the fact that they comprise the major part of the water surface of the area. Platvoet and Pinkster (1995) studied the distribution of various amphipod species in the Delta region in 1992 and found several talitrid and gammarid amphipod species along the Nieuwe Waterweg and adjacent harbours and the Nieuwe Maas. Ecological investigations have taken place within the harbours along the salinity gradient only on an ad hoc basis, for example the investigation of the flora and fauna of the littoral zone in Beer-, Caland- and Hartelkanaal and Nieuwe Waterweg by Paalvast (1998). This has led to some insight into the functioning of the harbours as an estuarine ecosystem, but due to the lack of consistency no deeper insight could be derived.

Outline of this thesis (Fig. 14)

Land reclamation, urbanisation, industrialisation and harbour development have radically changed the Noordrand as part of the Rhine-Meuse estuary from a soft to a hard substrate environment made of asphalt, stone, concrete, wood and steel. This environmental change from soft to hard is the underlying theme of this thesis.

From the middle of the 14th century to the construction of Maasvlakte 1 in the 1960s there was only awareness of the demands for shipping, port, industrial and urban development. Until the middle of the 19th century this had no serious consequences for estuarine nature, but with the industrial revolution this changed rapidly. In about one century, the ever changing dynamic estuary with its typical flora and fauna has been transformed into a massive hardened environment.
How and how quickly have these changes taken place? What characteristics of the estuary have been lost and what has come in its place? In **chapter 2**, the historical demise of the estuary using the disappearance of the estuary distinctive soft substrate ecotopes and the rise of hard substrate ecotopes related to port development, industrialization and urbanization is described.

The policy of the port of Rotterdam, international collaboration and a stricter environmental legislation drastically reduced the pollution of water and sediment. In particular the ban on the aggressive biocide TBT (tributyltin) from 1 January 2003 following the decision taken by the International Maritime Organisation has created possibilities for estuarine nature to recover. As water and sediment quality improved in the port area over the last decades, many plant and animal species have settled on the new hard substrates. The shipworm *Teredo navalis*, a wood boring bivalve mollusc is a threat to wooden structures in the port area, in particular fir and oak wood where many quays of the old harbours are build upon. The question is, is the shipworm still present in the port of Rotterdam area since its first appearance in the Dutch coastal waters in 1730 (Vrolik et al., 1860)? In **chapter 3** the distribution of this species in the port area and the growth of first year individuals in various types of wood are described.

The shipworm, *T. navalis*, drills in wood and depending on the type of wood may reach a length of 60 cm during its three year lifespan (Sordyl et al., 1998, Hoppe, 2002). But why it needs wood? Does it pierces in timber to use it as food or only to protect itself from predators. A stable isotope approach is used in **chapter 4** to answer to this question.

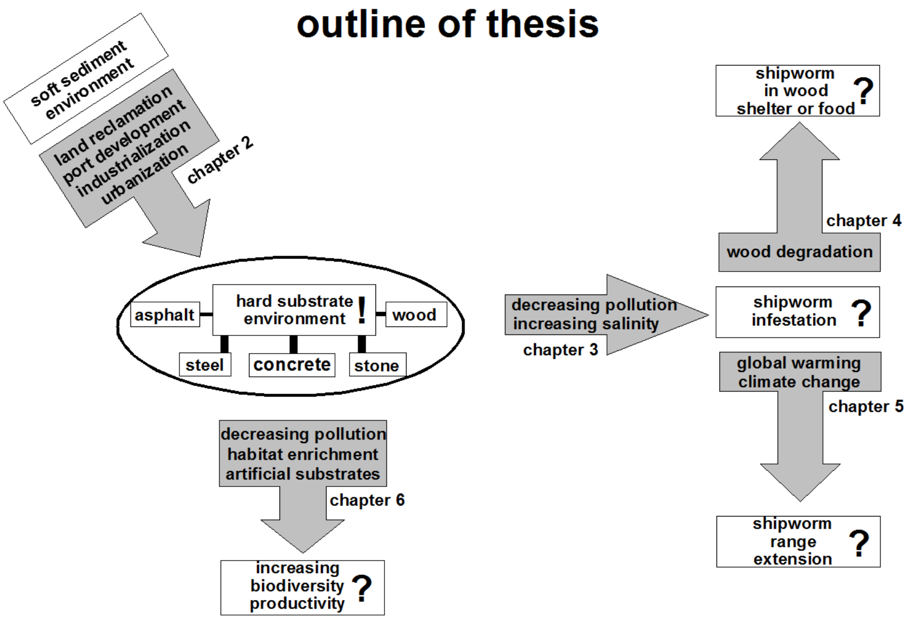

Figure 14 Schematic outline of the thesis.

Dredging for greater depth for shipping as mentioned above has led to a further penetration of the salt wedge stream upwards. At low river discharge brackish water penetrates the old harbours of the eastern part of the port of Rotterdam where quay walls are built on fir and oak piles. This might create conditions favourable for the shipworm to settle and grow. Climate change by global warming could result in long-term low to very low river discharges in summer. This may cause the shipworm to become a real threat to the stability of quay walls, but also for other structures made of wood, such as sluice gates and mooring poles. The sea level rise, also a consequence of climate change may exacerbate this.
But how serious will be the threat of the shipworm *T. navalis* to wooden structures in the harbours of the port of Rotterdam at global warming? In **chapter 5**, a risk analysis is made for damage caused by the shipworm in the

old harbours of the city of Rotterdam based on the KNMI (Royal Netherlands Meteorological Institute) climate change scenarios (Van den Hurk et al., 2007).

The harbours of the port of Rotterdam are designed exclusively for the berthing of ships and the transhipment of goods. No structural provisions are made neither intertidal nor subtidal for aquatic flora and fauna. A development of a stable soft bottom fauna by the ever continuing disturbance of the sea floor by dredging and boat propellers is impossible. However, with relatively simple means in sheltered environments, for example under jetties and pontoons, structure-rich habitats can be created, that might strengthen the biodiversity and productivity of the estuarine ecosystem of the port, now pollution is no longer limiting. One of the remedies could be rope structures around mooring poles and under pontoons and piers. The results of a pilot study described in **chapter 6** could bring clarity if habitat enrichment with this kind of structures really has an positive influence on biodiversity and -productivity in harbour systems.

In **chapter 7,** the outcome of the study is discussed in a broader perspective and compared with developments elsewhere.
Further improvements of the harbour environment by structural habitat enrichment are delineated that could make the port of Rotterdam a haven for estuarine nature.

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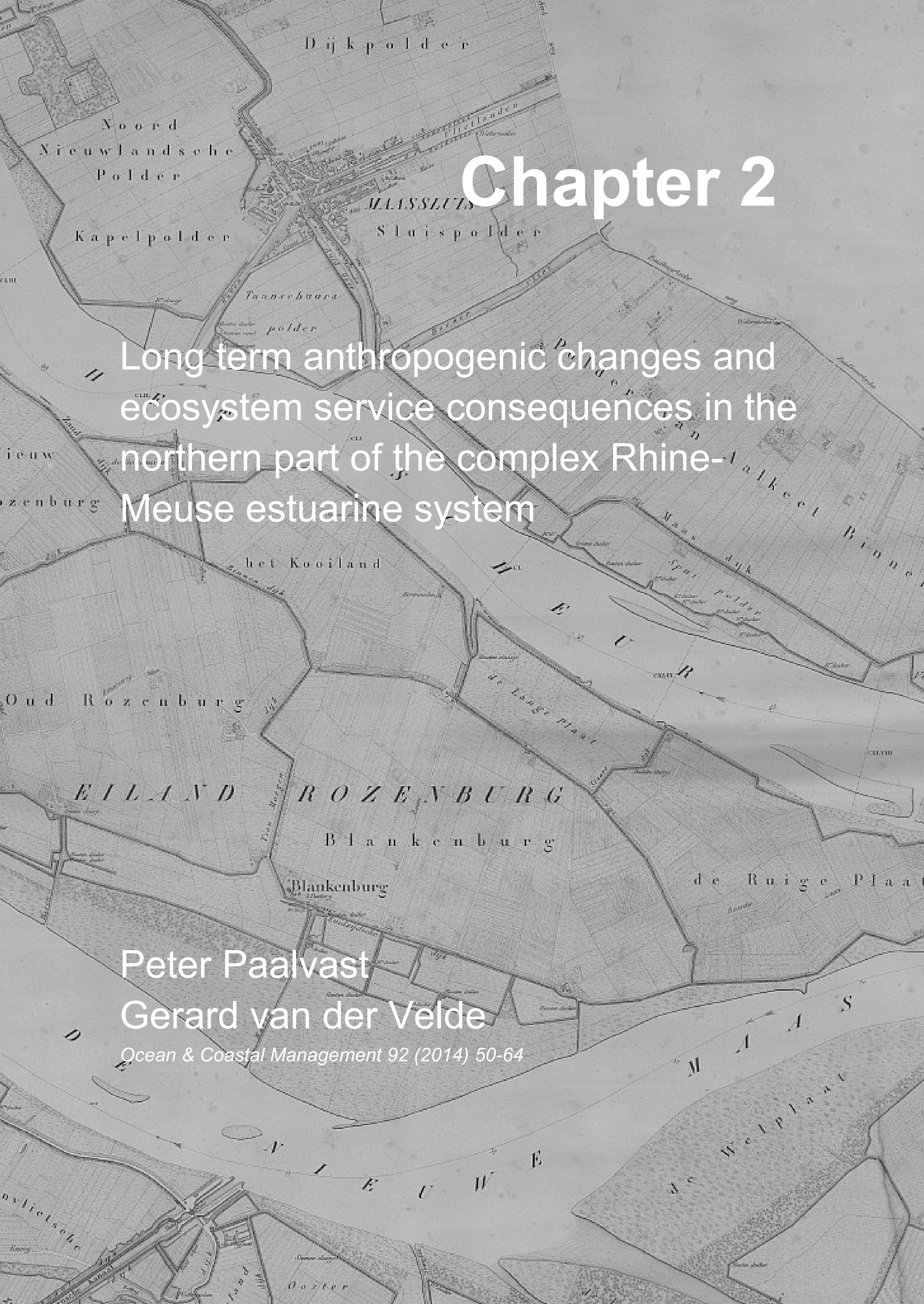

Chapter 2

Long term anthropogenic changes and ecosystem service consequences in the northern part of the complex Rhine-Meuse estuarine system

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Abstract

Around 0 AD, the Rhine-Meuse estuary in the southwest of the Netherlands was a typical coastal plain estuary. Drainage of peatland and land subsidence behind the dunes later caused the sea to penetrate into the land. Most of the peat was eroded, and by 1000 AD the so-called Delta area had turned into a landscape of large estuaries and intertidal zones. Rotterdam developed from a small fishing village on the banks of the tidal river “Nieuwe Maas” from the 14th century onwards into the largest seaport of Europe in 2013. The Rotterdam harbour area situated in the northern part of the Delta area includes the former Europoort harbour, and is nowadays known as Rijnmond. The hydrology of the area is controlled by the drainage regime of the sluices in the Haringvliet barrier that was constructed as part of the “Delta Works” project to protect the southwest of the Netherlands against storm surges. The sluices are opened at slack tide to discharge river water to the sea and are always closed at flood tide.

As a baseline study for environmental and ecological reconstruction and development, we describe in detail the loss of intertidal soft sediment ecotopes due to land reclamation, harbour development and river training works (straightening of the navigational channel) in the tidal rivers, and the expansion of hard substrate ecotopes (quay walls, groynes, training walls, riprap, concrete, stones etc.) in the Rijnmond area in the 19th and 20th centuries. Within 135 years, more than 99% of the original 4775 ha of characteristic pristine soft sediment estuarine ecotopes have disappeared. In the same period, 338 ha of hard intertidal substrate zone was constructed. Such trends can also be observed in harbour areas elsewhere, and have ecological and environmental consequences for estuarine areas in particular.

Restoration of soft substrate estuarine ecotopes can be achieved by opening the Haringvliet Sluices at both ebb and flood tide, which would restore large-scale estuarine dynamics to the northern part of the Rhine-Meuse estuarine system. This will have a highly favourable effect on many ecosystem services. The Dutch division of the Word Wild Life Fund has launched a new proposal for a safer and more attractive South-West Delta area. It comprises the reopening of the sea inlets such as the Haringvliet by removing the barriers, and building climate-proof dikes in combination with natural wetlands. In case of storm surges, the hinterland could be protected with a new generation of barriers that do not hamper the free transport of sediment, tides and animals. Based on 30 ecosystem services or subservices, it was calculated that opening the Haringvliet inlet would lead to an increase in Total Economic Value (TEV) of at least 500 million Euro per year. The costs of removing old barriers and the construction of new ones was not included in the calculations.

Introduction

General introduction

All over the world, coasts have been shaped after the Ice Ages, as sea levels rose during the Holocene. During this period, several estuaries were formed along the newly developing coasts of North-West Europe, through flooding of existing river valleys. This type of estuary, which is common in temperate regions, is called drowned river valley estuaries or coastal plain estuaries; they are often shallow and filled up with sediments, resulting in extensive mud flats and salt marshes (Dyer, 2002, McLusky and Elliott, 2004). In these new areas, islands could develop through heavy sedimentation of material transported from the river catchment areas. In addition, sediment from the sea, the coastal environment and erosion of the banks can also play a role in sedimentation processes and the distribution of sediment types in estuaries. Estuaries are further characterized by salinity fluctuations and gradients, where sea water and river water meet, as well as tidal and turbidity (suspended matter, flocculation) fluctuations and gradients. Coarse-grained sediment is deposited as bars near the mouth of the estuary, while finer-grained sediment penetrates upstream (Viles and Spencer, 1995). These processes originally led to ecologically valuable pristine estuarine wetlands developing as dynamically functioning ecosystems with high biodiversity and production (Barnes, 1974).

Estuaries have long been used by humans for various purposes. In the Netherlands, for example, the use of estuaries went through several phases in historical times (De Jonge, 2009). First people settled on the higher parts of the estuary, as there was less risk of flooding there, and they also built artificial dwelling mounds or terps to protect their homes against storm surges. The next step was to stabilize water courses by means of dikes or levees to protect homesteads and land against flooding. The next phase saw salt marshes as well as freshwater marshes being reclaimed and converted into polders for use as agricultural land. Later on, structures were built to prevent erosion of the littoral borders and the harbours and industrial sites, and further land reclamation followed. Harbours were made more accessible by dredging the water courses to deepen them. The consequences of this dredging activity have been widely studied, for example in the Ems (De Jonge, 1983, 2000, Schuttelaars et al., 2013, De Jonge and De Jong, 2002) and Elbe estuaries (ARGE ELBE, 2001, Fickert and Strotmann, 2007). The most recent phase has featured the creation of artificial sandy plains outside the former estuaries to enable the construction of marine harbours which can receive the largest ships.

Coastal and estuarine wetlands in North West Europe were settled by humans during the Neolithic Age. Major land management interventions such as ditched drainage systems and reclamation of salt marshes started during the Roman era (Rippon, 2000, Healy and Hickey, 2002) in particular in the south of Great Britain and the Netherlands. Systematic reclamation by means of embankment, resulting in large-scale loss of coastal and estuarine habitats, started in the 12th century (Wolff, 1992, 1993, Rippon, 2000) and continued until the second half of the 20th century. Airoldi and Beck (2007) give a comprehensive overview of the historical development of coastal wetlands in Europe, and they estimate an overall loss of more than 50% of the original surface area, with peak losses of over 80% in many regions. They estimated that between 1960 and 1995, one kilometre of European coastline a day was developed for human purposes alone. Land reclamation and dredging are considered to be more destructive to the estuarine ecosystem than the input and discharge of pollutants, as they lead to the disappearance of vital sedimentary habitats by coastal squeeze and changes in the hydrodynamic situation and associated sedimentation patterns (Doody, 2004, Hughes and Paramor, 2004, McLusky and Elliott, 2004).

Losses of estuarine ecotopes in the Netherlands

Large areas of moorland, swamp forest and salt marsh were reclaimed in the Netherlands between the 12th century and the second half of the 20th century (Wolff, 1993). The world's largest intertidal system, the "Wadden Sea" (Waddenzee in Dutch), which stretches along the coasts of the northern Netherlands, northwest Germany and west Denmark, has frequently been altered by humans since its origin 7500 years ago. The large-scale habitat transformations over the last 1000 years have had a major impact on its functioning as an ecosystem (Lotze et al., 2005), and during the last century in particular, human exploitation has transformed the intertidal areas from an internally regulated and spatially heterogeneous system to an externally regulated and spatially homogenous system (Erikson et al., 2010).

Two projects carried out in the Netherlands during the 20th century greatly reduced the size of the Rhine-Meuse estuary. The damming of the large northern inlet formerly known as the Zuiderzee (Fig. 1) was decided upon after a storm surge in 1916 had breached many dikes and inundated large areas around its shores (De Jonge, 2009). The 30 km long dike separating the Zuiderzee from the Wadden Sea was completed in 1932, and changed a 3700 km^2 estuarine area into a freshwater lake (De Jonge and De Jong, 1992). After the 1953 storm surge, which breached the dikes in 89 places in the south-west of the Netherlands, with the loss of 1836 lives, a huge flood protection scheme known as the Delta Project was proposed in the Delta Act, which was adopted by the lower chamber of the Dutch Parliament in 1957 and by the upper chamber in 1958 (Stuvel, 1956, 1961). The implementation of the Delta Project shortened the coastline by 700 km and resulted in the closure of most of the inlets of the Rhine-Meuse estuary by means of dams and sluices, and in the case of the Eastern Scheldt inlet and the Nieuwe Waterweg canal, by means of a storm surge barrier. An area of 890 km^2, comprising deep tidal water (446 km^2), shallow water (97 km^2), sand and mud flats (188 km^2), salt and brackish marshes (94 km^2), extensive reed and rush beds (40 km^2) and tidal willow coppices (tidal forest) (25 km^2) was lost or no longer part of the estuary (Wolff, 1992, Eertman, 1997, Paalvast et al., 1998). If these numbers are added to the losses due to land reclamation (3500 km^2) over the last 1000 years before the Delta Project, the total loss of estuarine ecotopes in the 5300 km^2 Delta Area is 83%, including the Western Scheldt inlet which was not closed. In 2011, less than 7% of the total area of the Rhine-Meuse estuary was left, relative to the 1950 situation. As entrances to the harbours of Antwerp and Rotterdam, the Western Scheldt inlet and Nieuwe Waterweg canal remained open, and only these waterways can be regarded as estuaries nowadays. From 1970, the Nieuwe Waterweg canal (excavated in the second half of the 19th century) was the only open connection left between the North Sea and the catchment areas of the rivers Rhine and Meuse.

Historical flood defence systems

The first dikes were protected against wave attack by rows of wooden piles (open-pile permeable groynes), which continued to be used until the years 1731/32, which saw massive destruction of the piles by the shipworm *Teredo navalis* (Vrolik et al., 1860). This led to a partial change in dike construction techniques, and by 1733 the dikes started to be protected by imported stones, which over the centuries led to “petrification” (hardening and consolidation of shores with riprap, stone, concrete and debris) of large parts of the Dutch coastline (including the estuaries) with hard-substrate defence structures. Similar measures were also taken in comparable areas in Europe from that time onwards. This ecotope was originally absent in the Netherlands and the hardening of the littoral zone created opportunities for rocky shore species to establish.

Petrifying trends in Europe

Different types of hard-substrate defences have led to severe petrification of dynamic sedimentary coastal areas in Europe (Airoldi et al., 2005). In addition, many estuaries (and rivers) became more or less petrified from the second half of the 19th century due to regulatory works involving groynes (mostly upstream) and training walls to maintain shipping lane depths, and due to shore protection with riprap or even debris from demolished buildings and roads. A striking

example is the mouth of the navigational channel in the Seine bay, where two large training walls have hardened and narrowed this part of the estuary by approximately 90% (Auger and Verrel, 1998).
The Port of Rotterdam is by far the largest port in Europe and was the world's busiest port between 1962 and 2004. It is an example of how in the past all estuarine nature in Europe was sacrificed for port development without any hesitation. This article describes the historical changes in soft-substrate areas and the petrification by means of stones, riprap, asphalt, concrete etc. of the northern part of the Dutch Delta Area, where the Rotterdam harbour is situated. It also discusses the prospects for recovery of the Rhine-Meuse estuarine ecosystem and its management in a local and an international context.

Materials and methods

Study area
The study was restricted to the northern part of the Delta Area (known locally as Rijnmond) in the southwest of the Netherlands (Fig. 1). To describe the changes in estuarine ecotopes (see section 2.2 for a definition), the estuary has been divided into three water systems with associated harbours (Figs. 1 and 5):

1. The Nieuwe Maas system, between Rotterdam at Rkm 996.3 (Rkm = river kilometre of the Rhine) and the confluence of the Oude Maas and Nieuwe Maas river near Vlaardingen.
2. The Scheur and Nieuwe Waterweg system (including the Hartelkanaal, Beerkanaal and Calandkanaal canals with associated harbours).
3. The Oude Maas, Hartelsche Gat, Botlek and Brielsche Maas system, including the mouth of the estuary.

Methods
An ecotope classification system has been developed for the larger water bodies in the Netherlands (Wolfert, 1996). Ecotopes are defined as "spatially delimited landscape units, whose composition is determined by the local abiotic, biotic and anthropogenic conditions."
Detailed digitized river and harbour maps were used to determine the changes in estuarine ecotopes and the petrification of the estuary in the northern part of the delta region between 1834 and 2010.
Data for the 1834-1835 period were derived from map numbers 17, 18, 19 and 20 of the "Algemeene Rivierkaart serie I" (General River Map, Series I) issued by the ministerial department of public works (Rijkswaterstaat, RWS) between

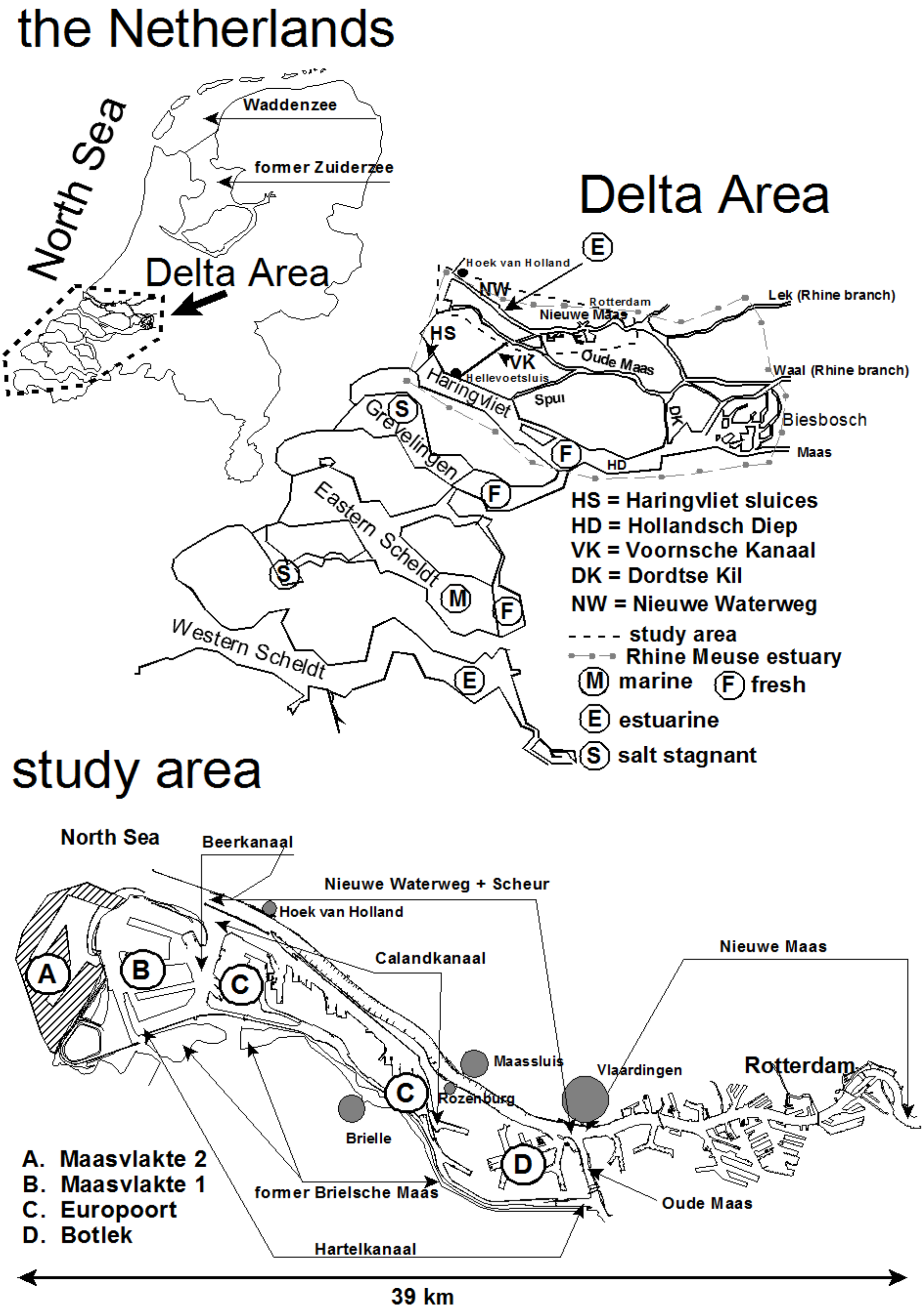

Figure 1 The location of the study area in the Delta Area in the Netherlands. The Lek, Waal and Oude Maas are distributaries of the river Rhine. Maas=Meuse.

1834 and 1835 at 1:10,000 scale (Rienstra, 1958, Boode, 1979, Van den Brink et al., 2002). Since these maps do not cover the mouth of the estuary, we estimated the ecotope surface areas in the mouth of the estuary by digitizing the map made by Von Wiebeking (1795) at a 1:40,000 scale.
Data for the 1877-1878 period were derived from map numbers 18, 19, 20, 21, 22 and 23 of the “Algemeene Rivierkaart, Eerste Herziening, Serie I” (General River Map, First Revision, Series I) issued by Rijkswaterstaat between 1880 and 1881, at a 1:10,000 scale (Boode, 1979, Van den Brink et al., 2002).
Data for the 1933-1935 period were derived from map numbers 20, 21 and 22 of the “Algemeene Rivierkaart, Tweede Herziening, Serie I” (General River Map, Second Revision, Series I) issued by Rijkswaterstaat between 1942 and 1945 at a 1:10,000 scale, and map numbers 17 to 29 of the “Algemeene Rivierkaart, Tweede Herziening, Serie II” (General River Map, Second Revision, Series II) issued by Rijkswaterstaat between 1933 and 1937, at a 1:5,000 scale (Boode, 1979, Van den Brink et al., 2002).
Data for the 2000-2010 period were derived from the digital map of ecotopes of the region at a 1:5,000 scale, produced by Rijkswaterstaat (Anonymous, 2000), and the digital map of the Rotterdam harbour area, at a 1:20,000 scale, issued by the Port of Rotterdam Authority (2006), in combination with designs for the banks at a 1:500 scale and “Google Earth”.
It should be noted that the old river maps were all drawn on the basis of the mean low water level.

The following ecotopes were distinguished on these maps:

a. *Natural open water at mean low water level* (MLW): rivers, tidal creeks, gullies.
b. *Artificial open water at MLW*: harbours
c. *Soft substrate in the intertidal zone* (between MLW and HWS = maximum spring tide high water level): estuarine meadows, tidal willow coppice, reed beds, rush beds, mud flats, sand flats and beaches.
d. *Hard substrate in the intertidal zone* (between MLW and HWS): quays and riprap in harbours, groynes, piers, riprap and rockfill along rivers.
e. *Soft substrate above HWS*: dunes, open sand flats

The surface areas covered by these ecotopes and the lengths of the banks of rivers, creeks, gullies and quays were measured on-screen with the aid of the spatial data builder Cartalinx by Clark Labs.

The zonation of the ecotopes is shown in figure 2.
In this article, estuarine means that part of the river where the tide is still noticeable and that part of the sea where there is still river influence. It includes the freshwater tidal area and the tidal area with a gradient from fresh river water to seawater.

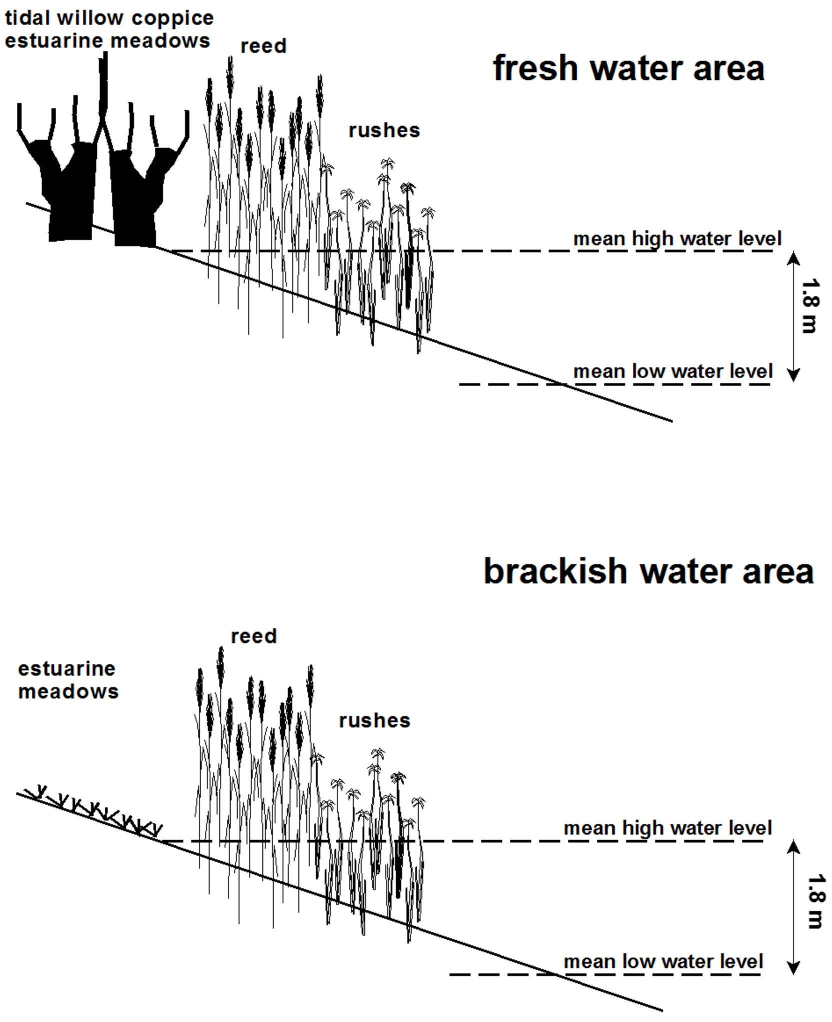

Figure 2 Zonation of ecotopes in the fresh and brackish water part of the Rhine-Meuse estuary.

Estuarine meadows. The estuarine meadows are found in the zone with the lowest tidal inundation frequency. This ecotope was in use as extensively managed grasslands and hayfields. They were the richest amongst the soft substrate intertidal ecotopes in terms of biodiversity, with hundreds of plant (Melman et al., 1997) and macroinvertebrate species (Van der Velde, unpublished data) and many breeding and foraging bird species (Strucker et al., 1994). The composition of the communities changed gradually along the salinity gradient from fresh to brackish.

Tidal willow coppice (called *grienden* in Dutch). This ecotope can be regarded as replacing the original tidal forests, and is found in the freshwater part of the estuary. The practice of coppicing willow trees in the Rhine-Meuse estuary dates back as far as the 13th century (Wolf et al., 2001). The osiers were used for baskets, fykes, beanpoles, helves, hoops for butter casks and herring barrels, furniture, Dutch mattresses, shore defence etc. (Wisboom van Giessendam, 1878). The most common trees used for this purpose are *Salix viminalis* (Common Osier) and *S. alba* (White Willow). *S. dasyclados* is usually the only tree in the parts of the coppices with the longest duration and highest frequency of inundation. Although these coppices are not rich in numbers of plant species, their undergrowth houses unique species such as *Cardamine amara* (Large Bitter-cress)*, Leucojum aestivum* (Summer Snowflake) and *Caltha palustris* subsp. *araneosa* (Marsh-marigold). The coppices are important for many bird, fish and macroinvertebrate species (Adriani, 1977, Wolf et al., 2001).

Reed beds. This ecotope, consisting mainly of *Phragmites australis* (Common Reed) is found in both the freshwater and brackish parts of the estuary. Most of the reed beds have been cultivated for use in mats, baskets, furniture and roofing. Among the reeds in the freshwater parts of the estuary, there are large numbers of specimens of *C. palustris* subsp. *araneosa* in the lowest zone of the beds, while *C. amara* determines the aspect higher up. Both species are replaced by *Cochlearia officinalis* subsp. *officinalis* (Common Scurvygrass) when the inundating water becomes brackish (Paalvast, 1995). Reed beds are a habitat for many invertebrates and birds (Weeda et al., 1994) and a feeding ground for crustaceans and fish at high tide.

Rush beds. The rush beds are the lowest vegetated ecotope of the intertidal zone of the freshwater and brackish water parts of the estuary. The rushes used to be cultivated for mats, chair seats and sealing of barrels. The rhizomes of the rushes were often planted on newly accreted sediment to promote sedimentation, as a first step towards land reclamation (Bakker and Boer, 1954, Smit and Coops, 1991). In the freshwater part of the estuary, the rush beds show a high-to-low zonation going from *Bolboschoenus maritimus* (Sea Club-rush), via *Schoenoplectus lacustris* (Common Club-rush or Bul-rush) to

Schoenoplectus triqueter (Triangular Club-rush). The latter is the most characteristic plant of the freshwater tidal area in the Netherlands (Weeda et al., 1994). *S. triqueter* does not occur in the brackish zone, while *S. lacustris* is gradually replaced by *S. tabernaemontani* (Grey Club-rush). Rushes are an important food source for herbivorous birds and a feeding ground for crustaceans and fish at high tide.
Sand flats and beaches. This ecotope is found in the intertidal zone with the strongest hydrodynamics. The sand flats and sand bars are important feeding areas for waders at low tide and for fish and crustaceans at high tide.
Mud flats. This ecotope develops at lee sites with considerable hydrodynamics, where it fulfils the same ecological role as sand flats.
Open sand flats above HWL. This ecotope consists of bare sand and is characterized by pioneer species such as *Elytrigia juncea* subsp. *boreoatlantica* (Sand Couch) and *Euphorbia paralias* (Sea Spurge), as well as by juvenile dunes. They are very important for ground-breeding seabirds (Van Beusekom et al., 1930).
Dunes. The dunes form an ecotope out of direct reach of the estuarine water. Due to their complexity of habitats, with large differences in abiotic conditions, in which salt spray plays an important role, the variety of plant and animal species is the highest of all ecotopes in the estuary.
Hard intertidal substrate. All of the hard substrate of this ecotope in the estuary has been introduced by man. Large parts of it consist of bare concrete, limestone, basalt etc. In the freshwater and oligohaline parts of the estuary, it can be covered by small green algae, while a dense cover of *Fucus vesiculosus* (Bladder wrack), a brown alga, may occur in the meso- and polyhaline parts.

Results

The main events in the area are summarized in Table 1.

Changes in the study area (Rotterdam Harbour) between 0 AD and 1830 AD
Around 0 AD, the mouth of the river Meuse was a truncated estuary with a length of 30 km and a width of some 10 km at its outlet into the sea (Fig. 3). The estuary was fed by water from the Rhine and Meuse and some peatland rivers. The coastline of southwest Holland was more or less closed and only interrupted by a few estuaries. Drainage of peatland and land subsidence behind the dunes caused the sea to penetrate into the land. Most of the peat was eroded and by 1000 AD, the Delta area had turned into a landscape of large estuaries and intertidal zones (Zagwijn, 1991, Mulder et al., 2003).

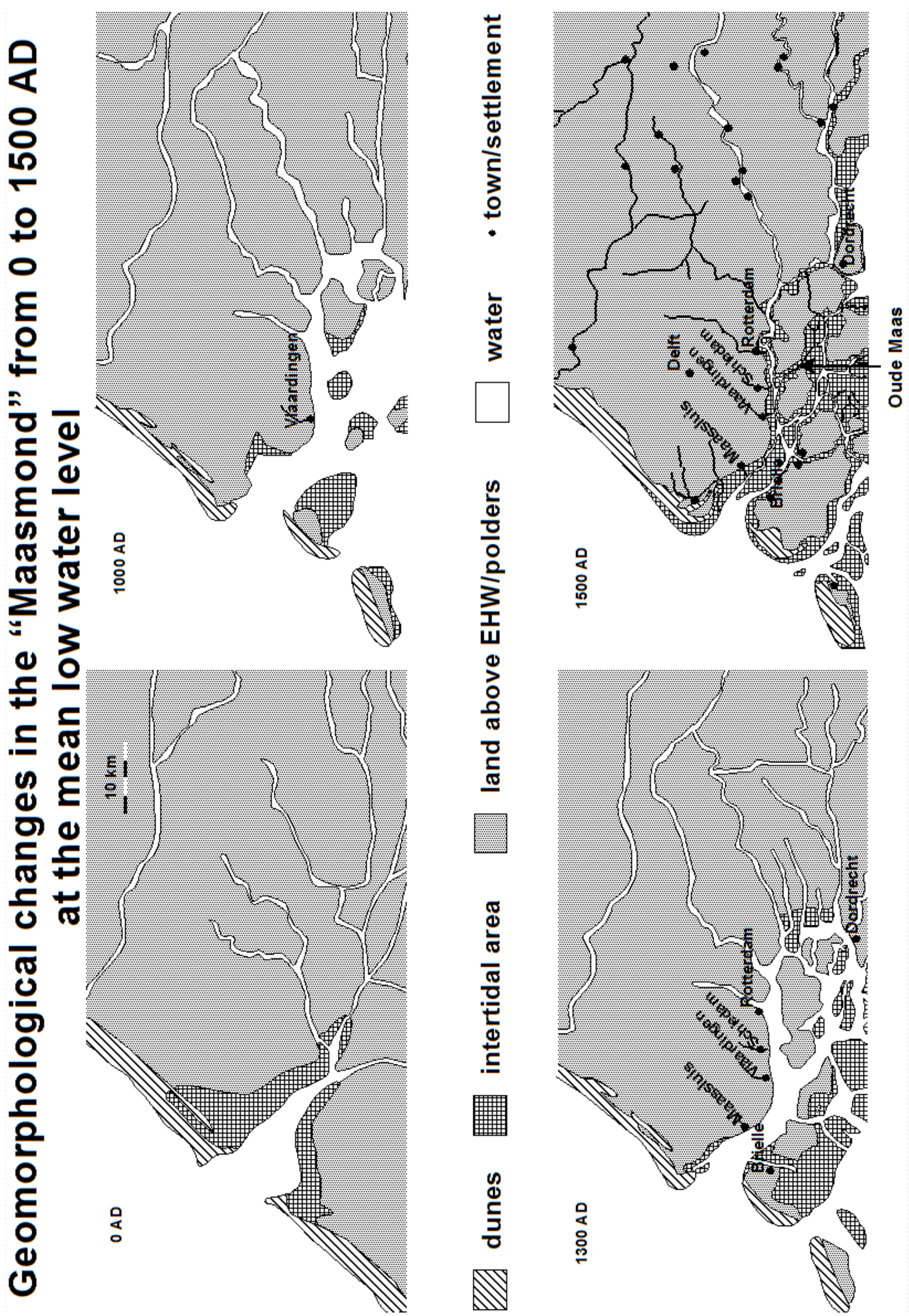

Figure 3 Geomorphological changes at the mean low water level in the "Maasmond", the mouth of the Rhine-Meuse estuary between 0 and 1500 AD (after Zagwijn, 1991). EHW = extreme high water level.

Vlaardingen, the oldest known human settlement in the area (2900 BC to 2600 BC; Rippon, 2000), was founded as a village around 800 AD. The first harbours were located at the mouths of peatland rivers that have either been dammed or have disappeared over time. The towns of Brielle, Schiedam and Rotterdam were founded in the 13th, Delfshaven (the harbour of the town of Delft) and Maassluis in the 14th century (Fig. 3). Rotterdam (named after a dam built in a small tidal peatland river called “Rotte”) developed in the 14th century from a small fishing village on the banks of the “Nieuwe Maas” tidal river, and later became a seaport.

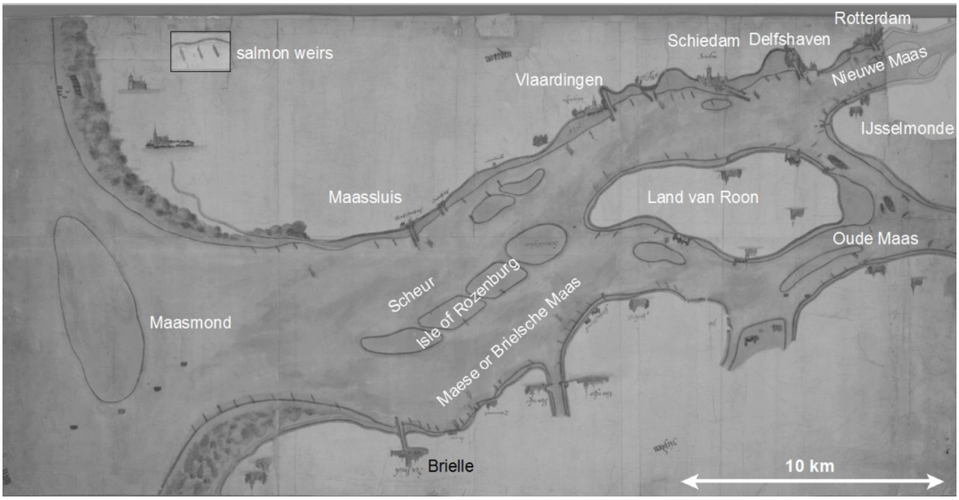

Figure 4 Map of the northern part of the Rhine-Meuse estuary around 1500 AD (author unknown).

From the 12th to the 14th century, large parts of the intertidal zone were reclaimed, reshaping this part of the open estuary once more into a more truncated one (Fig. 3). The construction of dikes along the rivers and the damming of river branches around the 15th century meant that the bulk of the Rhine and Meuse water came to be discharged via the “Oude Maas” river to the mouth of the river Brielsche Maas (“Maasmond”) (Fig. 4) (Ploeger, 1992, Ten Brinke, 2005). A storm surge known as “Sint Elisabethsvloed” in 1421 created an inland sea, which has by now developed into the marshland area called Biesbosch (Fig. 1). The main cause of the disaster was peat extraction all the way to the foot of the dikes, resulting in “piping”. After this flood event, most of the water of the river Waal discharged via the new inland sea towards the Hollandsch Diep-Haringvliet inlet. In the mouth of the river Brielsche Maas (Fig. 4), the river discharge fell to 25% of its original value, leading to increased

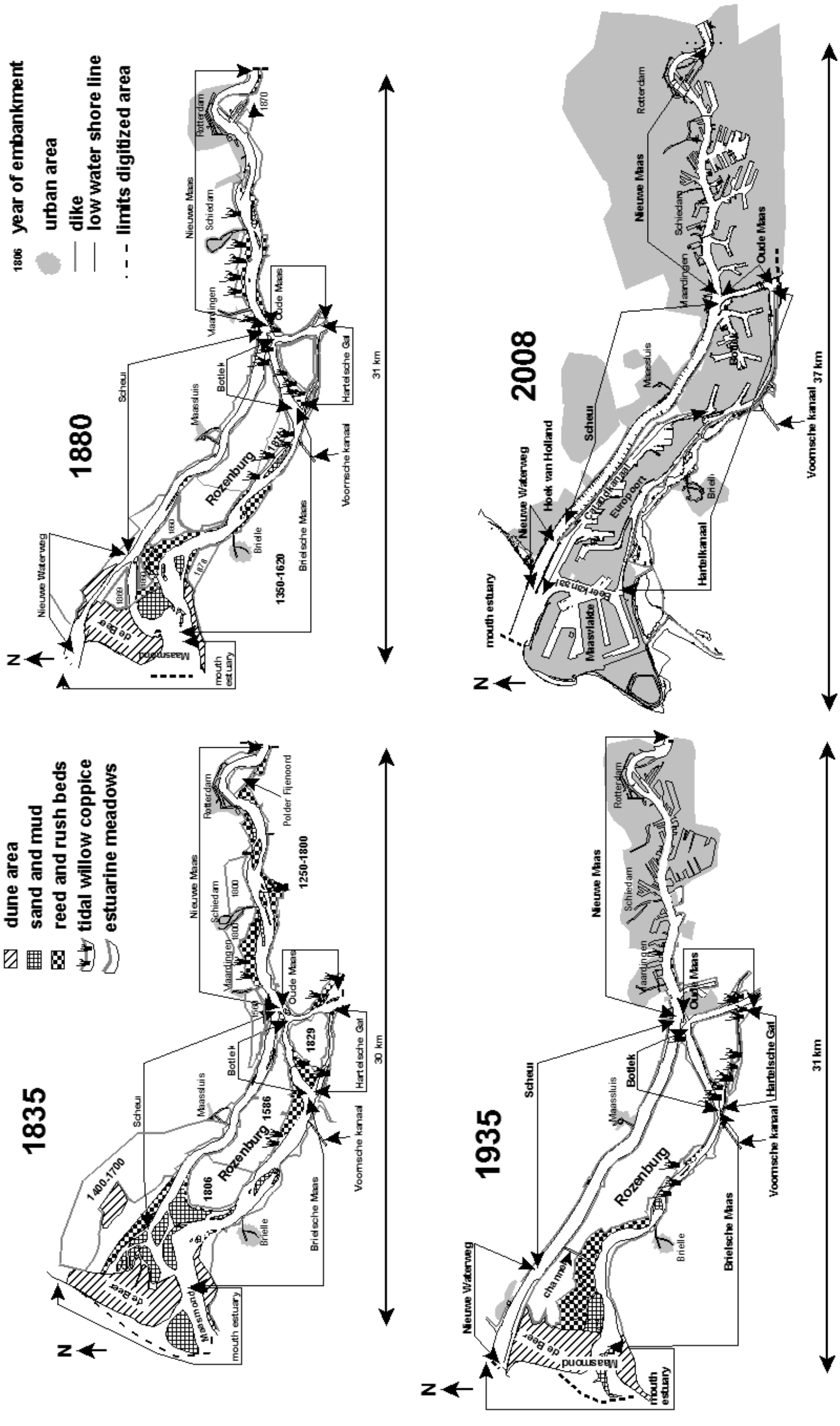

Figure 5 Changes of estuarine ecotopes between 1835 and 2008 in the Rhine-Meuse estuary.

Table 1 Main events in the northern part of the Rhine-Meuse estuary.

period/year	event
800	founding of Vlaardingen
11th century	first dikes along the rivers
12th till 20th century	land reclamation on a large scale
13th century	founding of Brielle, Schiedam, Rotterdam
14th century	founding of Delfshaven, Maassluis
1421	St-Elisabeth flood resulting in an inner sea where now is the Biesbosch
1586	first embankment in the mouth of the estuary, creation of the isle of Rozenburg
1658	appointment of a permanent commission by the city of Rotterdam to monitor salmon weirs in the river
1830	opening of the Voornsche Kanaal, a navigational channel for Rotterdam
1866-1872	excavation of the Nieuwe Waterweg
1932	closure of the Zuiderzee after storm surge in 1916
1950-1953	closure of the Brielsche Maas
1954-1960	Botlek harbour and industrial area
1956-1997	Delta project, closure of Delta area after storm surge in 1953
1957-1968	Europort harbour and industrial area
1965-1970	Maasvlakte 1 harbour and industrial area
2008-2013	Maasvlakte 2 harbour and industrial area

sedimentation. Large sandbanks and mud flats were formed from sediments of the now slow-flowing river, which split the truncated estuary into two parallel tidal rivers, called Scheur and Brielsche Maas (Maese). The water was slowed down further by the large number of places where salmon weirs (*zalmsteken* in Dutch; fascine wood structures to which large fyke nets were attached; see Fig. 4) were placed perpendicular to the flow, up to 110 metres into the river. To cope with this problem, the local government of Rotterdam decided in 1658 to appoint a permanent commission that had to monitor this type of fishing (Wouda, 2007). The first embankment in this part of the river mouth was completed in 1586 (Kuipers, 1962) creating the island of Rozenburg (Figs. 4 and 5). Sedimentation and accretion continued, not only by sediment from the sea but also as a result of large-scale logging (clear-felling) on the banks in the middle reaches of the river Rhine in the 17th century (Wouda, 2007). Although ships sailed between the

North Sea and Rotterdam and vice versa along the Brielsche Maas and Scheur, this was not without risk and only possible with shallow draught ships. From the 18th century on, large vessels could no longer use the Brielsche Maas and Scheur at low tide (Kuipers, 1962, Buijsman, 2007). The cargo had to be transhipped at the town of Hellevoetsluis on the Haringvliet inlet, into smaller ships that could more easily sail to Rotterdam. Alternative routes via Haringvliet/Grevelingen-Hollandsch Diep-Dordtse Kil-Oude Maas-Nieuwe Maas (Fig. 1) were used up to the first half of the 18th century, but these waterways silted up, making access to the port of Rotterdam more and more difficult. Sailing to and from Rotterdam by these routes took several days and sometimes several weeks (Buijsman, 2007). The “Voornsche Kanaal”, a canal excavated through the island of Voorne, was opened in 1830 (Kuipers, 1962). Ships could now use the canal and continue their journey to Rotterdam via the section of the river Meuse called Botlek (Figs. 1 and 5).
From around 1300 to 1600, the surface area covered by the harbour grew from 8 to 20 ha, mainly at Rotterdam (Fig. 6). In the beginning of the so-called Golden Age of the Netherlands (1600) the harbour area doubled to 40 ha over a period of 30 years, thanks to shipping to tropical regions and the Baltic. The size of the harbour area then remained unchanged until the start of the industrial revolution around 1850.

The state of estuarine ecotopes in the Rotterdam harbour area around 1835

Until 1835, urbanization and industrialization had only taken place on a small scale on the northern bank of the river Nieuwe Maas, particularly at Rotterdam (Fig. 5). Fifty-eight percent (1536 ha) of the total estuarine area of the Nieuwe Maas was occupied by the tidal river, 38% by soft substrate intertidal ecotopes, 4% by harbours and less than 1% by hard substrate intertidal ecotopes, mainly quays (Fig. 7, Table 2). The lower part of the river banks consisted of sand flats, and in sheltered places also mud flats. Reed and rush beds and tidal willow coppice were the most important estuarine ecotopes, with a total area of some 500 ha. Two small and six larger sandbanks were situated in the riverbed.
Along the river Scheur, with a total estuarine area of 1683 ha (river and harbour water surface and hard and soft estuarine ecotopes) stretching to the west end of the island of Rozenburg, soft estuarine ecotopes were already scarce (Fig. 7), due to land reclamation activities carried out here since the 15th century (Figs. 5 A and B); they consisted of a narrow strip of estuarine meadows adjoining the sea dikes. The shores were protected by riprap in several places, covering a total intertidal surface of 2 ha. However near the confluence with the river Brielsche Maas, there were many large sand and mud flats, reed and rush beds, estuarine meadows and dunes, covering 75% of this part of the estuarine area.

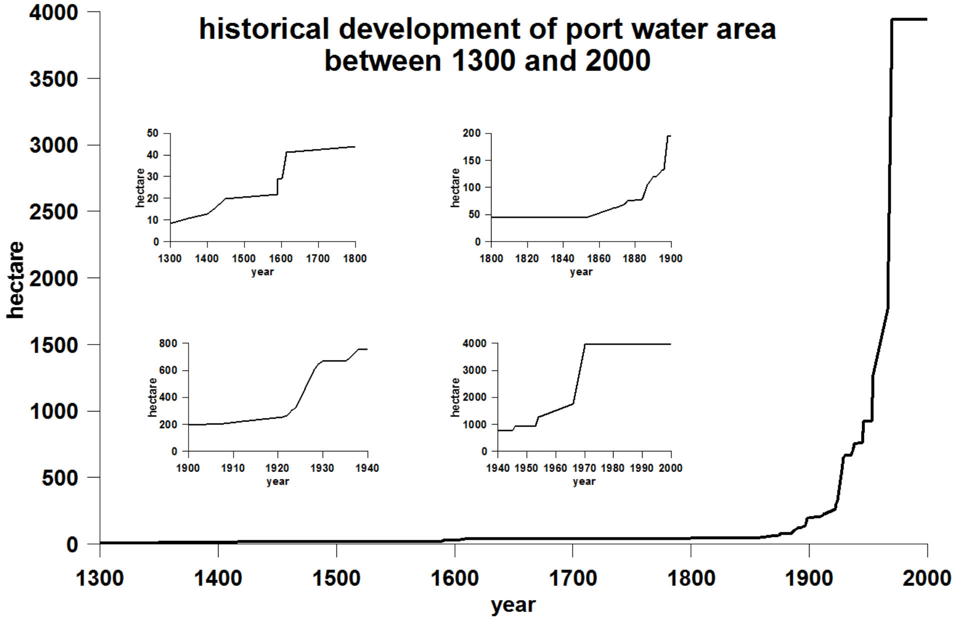

Figure 6 Historical development of the port water area in the northern part of the Rhine-Meuse estuary between 1300 and 2000.

The Brielsche Maas water system, with a total estuarine surface of 5154 ha, was characterized upstream by a considerable area of tidal willow coppice and large reed and rush beds that changed into sand and mud flats near the mouth of the estuary (Fig. 5). Since the end of the Middle Ages, sedimentation had led to a large dynamic area of beaches, sand and mud flats, dunes, reed and rush beds and salt marshes, called “De Beer” (the Bear) or the “Hook of Holland”, with a size of 1500 ha (Fig. 5). Salt marshes were not indicated on the maps, but they must have been present, covering an area of 200 to 300 ha, as they still existed around 1960 (Buijsman, 2007). A map drawn by Jacobsz (1633) also suggests the presence of salt marshes near the mouth of the estuary. The intertidal zone and the dunes together comprised 62% of the total area, the tidal river 38% and tidal harbours a mere 0.1 % (Fig. 7, Table 2).
Data presented by Haring (1977) show that of the average discharge of the Rhine and Meuse together (2400 $m^3 s^{-1}$), some 850 $m^3 s^{-1}$ would have been discharged via the Scheur and Nieuwe Maas. The Maasmond must therefore have been a polyhaline area. In the upstream parts of the Scheur and Brielsche Maas, this would gradually have changed to oligohaline conditions, with the Nieuwe Maas and Oude Maas rivers constituting a freshwater tidal area.

Table 2 Development of river and port area in hectares (ha = 10,000 m^2), river length, shoreline and intertidal ecotopes in the northern part of the Rhine-Meuse estuary between 1834-35 and 2008.

		Nieuwe Maas				Scheur/Nieuwe Waterweg			
item	unit	**1834-35**	**1880-81**	**1933-35**	**2008**	**1834-35**	**1880-81**	**1933-35**	**2008**
river surface	ha	884	899	695	715	683	1111	1254	1477
port surface	ha	57	74	703	907	9	9	12	3035
river length	km	16.5	16.2	15.7	16.4	13.7	20.9	21.7	22.7
length soft river shoreline	km	250.0	234.6	24.2	0.3	138.0	208.7	14.9	0.8
length hard river shoreline	km	11.3	25.9	26.9	30.7	0.5	5.4	52.6	52.3
length soft port shoreline	km	0.8	0.0	15.4	0.0	3.3	1.7	0.3	0.0
length hard port shoreline	km	22.9	30.6	74.2	90.8	2.1	3.9	9.5	162.4
total length soft shoreline	km	250.8	234.6	39.6	0.3	141.3	210.5	15.3	0.8
total length hard shoreline	km	34.2	56.5	101.1	121.5	2.6	9.3	62.2	214.7
surface soft intertidal ecotopes	ha km^{-1}	35.3	8.2	4.4	0.0	72.3	33.9	8.3	0.7
surface hard intertidal ecotopes	ha km^{-1}	0.7	1.0	2.9	4.1	0.1	0.5	2.0	11.7
		Brielsche Maas water system				**total area**			
item	unit	**1834-35**	**1880-81**	**1933-35**	**2008**	**1834-35**	**1880-81**	**1933-35**	**2008**
river surface	ha	1976	2029	1288	109	**3543**	**4039**	**3237**	**2301**
port surface	ha	8	8	5	0	**74**	**90**	**719**	**3942**
river length	km	29.2	28.6	30.0	3.2	**59.3**	**65.6**	**67.4**	**42.3**
length soft river shoreline	km	451.7	443.6	628.7	0.0	**839.7**	**886.9**	**708.3**	**1.1**
length hard river shoreline	km	0.6	6.0	6.5	7.6	**12.5**	**37.4**	**86.0**	**90.6**
length soft port shoreline	km	0.5	0.0	0.0	0.0	**4.6**	**1.7**	**15.8**	**0.0**
length hard port shoreline	km	4.3	5.8	4.3	0.0	**29.2**	**40.3**	**88.1**	**253.2**
total length soft shoreline	km	452.2	443.6	628.7	0.0	**844.3**	**888.6**	**724.0**	**1.1**
total length hard shoreline	km	4.9	11.9	10.8	7.6	**41.7**	**77.7**	**174.1**	**343.9**
surface soft intertidal ecotopes	ha km^{-1}	108.6	62.2	73.3	0.0	**79.9**	**39.9**	**36.3**	**0.4**
surface hard intertidal ecotopes	ha km^{-1}	0.1	0.2	0.2	1.9	**0.3**	**0.5**	**1.4**	**8.0**

A look at the total area shows that there was an estuarine area of 8372 ha, 42% of which consisted of tidal river, 1% of tidal harbour, 57% of soft substrate ecotopes and only 0.2% of hard substrate ecotopes (Fig. 7, Table 2).

The state of estuarine ecotopes in the Rotterdam harbour area around 1880

Only a few decades after the “Voornsche Kanaal” canal came into use, it had already become too narrow for the new steam-driven ships, and problems of navigation also arose as the entrance to the Haringvliet inlet silted up (Kuipers, 1962). The solution was found in constructing the Nieuwe Waterweg canal through the “De Beer” area, damming the Scheur at its confluence with the Brielsche Maas, directing the river water from the Oude Maas into the Scheur and normalizing the river (i.e. straightening its navigational channel) with the help of groynes (Anonymous, 1885). The project started in 1866 and the 4.3 km Nieuwe Waterweg was finished in 1872, connecting the river Scheur to the sea (Fig. 3), so that Rotterdam became easily accessible to steam ships.

The harbours of Rotterdam expanded along the river Nieuwe Maas by some 30% between 1850 and 1880 (Table 2), predominantly on the southern bank of the river, in the polder called Fijenoord (now named Feijenoord) a former island in a bend of the river (Fig. 5). River training works and land reclamation had caused large parts of the vegetated intertidal zone to disappear, viz. 80% of the reed and rush beds and 70% of the tidal willow coppice. The less frequently inundated estuarine meadows were reduced by 30%, and the area covered by sand and mud flats fell by 70%. Around 1880, three small and four partly vegetated larger sand banks were still present, but they were removed soon after by dredging. The total size of the estuarine area was reduced by 27% to 1122 ha.

The excavation of the Nieuwe Waterweg and river training works caused a further reduction of the estuarine meadows that had been reclaimed along the river Scheur, as well as a loss of dune area, whereas the water area increased by over 400 ha to 1111 ha (Table 2). A temporary 85 ha mud flat area developed in the part of the Scheur that was separated from the Maasmond by a dam. The hard intertidal substrate, in the form of groynes and shore defences, increased by over 400%, to 11 ha. The discharge of river water under average conditions (data derived from Haring (1977)) totalled 350 $m^3\ s^{-1}$, which must have created a transition zone from polyhaline conditions at the sea mouth to oligohaline conditions in the Nieuwe Maas.

Land reclamation between 1850 and 1880 had a tremendous impact on the estuarine ecotopes of the Brielsche Maas water system. The water surface increased by 3%, but the total estuarine area (including the tidal river and harbour area) decreased by 26% from 5154 ha to 3818 ha. Estuarine meadows

shrank by 70%, reed and rush beds by 80%, mud flats by 85% and sand flats and beaches by 40%. Tidal willow coppice increased by more than 150% as reed and rush beds were turned into coppices. The area of bare sand situated above the high water level and that of the dunes remained the same. Although the harbour was not expanded further between 1835 and 1880, the hard intertidal substrate increased from 2 to 5 ha. The discharge of river water under average conditions (data derived from Haring (1977)) in the Maasmond dropped from 850 m^3 s^{-1} to 450 m^3 s^{-1} after the Nieuwe Waterweg (350 m^3 s^{-1}) was excavated and the Scheur was dammed off. This must have led to a significant increase in the salinity of the river Brielsche Maas, especially the Maasmond part, favouring saline flora and fauna in the ecotopes.
Between 1835 and 1880, the total natural estuarine area shrank by 19% from 8377 ha to 6780 ha. The decrease was mainly caused by the disappearance of more than half of the area of soft estuarine ecotopes by land reclamation. In 1880, the estuarine area consisted of 60% tidal river area, 1.3% tidal harbour area, 39% soft estuarine ecotope and 0.5% hard estuarine ecotope (Fig. 7, Table 2).

The state of estuarine ecotopes in the Rotterdam harbour area around 1933-35
Between 1880 and 1900, the harbours along the river Nieuwe Maas expanded by 120 ha to cover a total of 195 ha (Fig. 6). Between 1900 and 1938, a further 550 ha of harbours were constructed on both the southern and northern banks of the river (Fig. 5), and just before World War II, the area of tidal harbours exceeded the area of the river channel itself (Table 2). Compared with 1880, the total estuarine area had grown by 392 ha, but the soft estuarine ecotopes had been reduced by almost 50% to 70 ha (a factor of 8 compared to 1835), whilst the hard intertidal substrate in the Nieuwe Maas area had nearly tripled in area to 46 ha (Fig. 7). The river training was almost completed, the shoreline had been turned into a stony environment with only a few small areas of soft estuarine ecotopes in direct contact with the river downstream of Rotterdam.
Soon after the Nieuwe Waterweg came into use in 1877 it started to silt up, as did the river Scheur, and new regulatory works (mainly groynes) and dredging had to be carried out to cope with the problem for shipping (Anonymous, 1880). Furthermore, the mouth of the Nieuwe Waterweg became narrowed, while the river Scheur widened (Ploeger, 1992) and the discharge of river water increased to 690 m^3 s^{-1} (under average conditions) (Haring, 1977). The soft estuarine ecotopes, in particular the estuarine meadows, were reduced by 75% compared to 1880, to a size of 179 ha, while the area of hard-surface estuarine ecotopes along the Nieuwe Waterweg and Scheur quadrupled to 44 ha. The tidal harbour area showed a relatively slight increase of 3 ha, to a total of 12 ha.

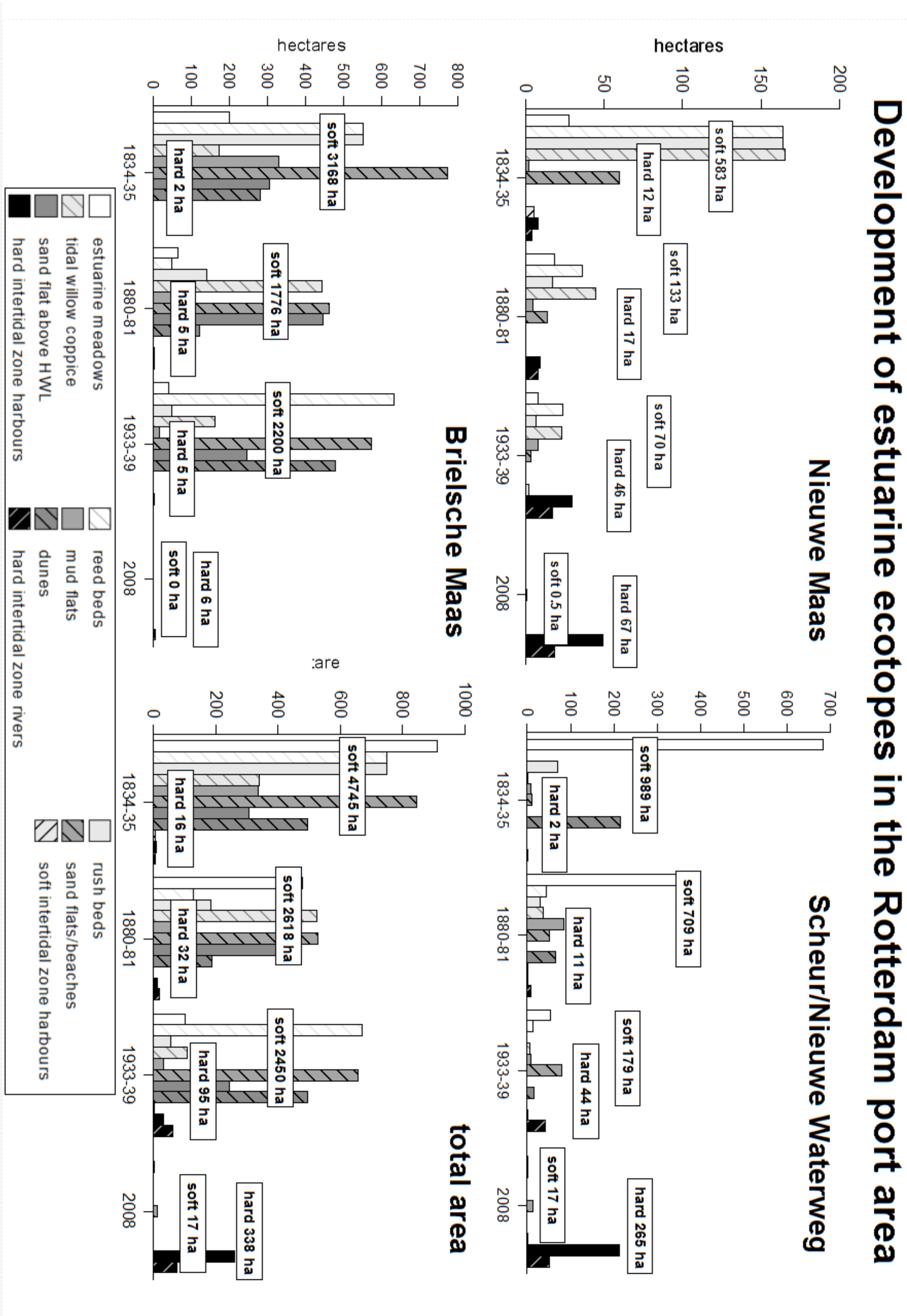

Figure 7 Development of estuarine ecotopes in the Rotterdam port area (nowadays called Rijnmond).

Between 1880 and 1939, the Brielsche Maas water system silted up, mainly at the Maasmond. No dredging took place, on the contrary, sediment dredged from the Scheur was transported via a canal through Rozenburg and deposited along the north bank of the Brielsche Maas opposite the town of Brielle (Fig. 5). Compared to 1880, the total estuarine area shrunk slightly, by some 8%, to 3498 ha. Sedimentation reduced the tidal water area by 37%, while the area of soft estuarine ecotopes grew by 24%. Reed beds increased substantially, as did sand flats and dunes. The size of the hardened estuarine littoral ecotope area changed little (Fig. 7).
Compared to 1880, the total estuarine area shrank by 4% to 6501 ha. It consisted of 50% tidal river area, 11% tidal harbour area, 38% soft estuarine ecotope and 1.5% hard estuarine ecotope.

The state of estuarine ecotopes in the Rotterdam harbour area in 2008
Before 1950, the harbour area on the southern bank of the river Nieuwe Maas was extended by some 200 ha (Fig. 6). This extension meant that the last soft substrate intertidal ecotopes disappeared, and all the riverbanks were turned into quays, riprap, concrete debris, rockfill and other hard substratum. In 2008, there was only one small artificial beach left, with a size of 0.5 ha. Within the 1690 ha estuarine area, tidal harbours covered 54%, rivers 42%, hard substrate intertidal ecotopes 4% and soft substrate intertidal ecotopes no more than 0.03%.
The Scheur and Nieuwe Waterweg also underwent dramatic changes. The 12 ha harbour area increased by 350 ha in 1954, as the Botlek waterway was converted to a harbour system and industrial area (Fig. 6). Expansion went on and between 1957 and 1968, most of the island of Rozenburg underwent the same fate and became Europoort, a large petrochemical industrial and port area. But before the Europoort harbour was completed, the construction of a new harbour complex on an artificial sandy plain, called Maasvlakte started in 1965; it was completed in 1975 (Fig. 5 D), adding 2670 ha of tidal harbour to the Scheur and Nieuwe Waterweg water system (Fig. 6). The hard substrate intertidal zone expanded by a factor of 6 from 44 ha to 265 ha, and almost all the soft estuarine ecotopes disappeared. What was left in 2008 were some beaches and sand flats behind training walls at Hook of Holland (12 ha), a man-made reed and rush bed in a harbour in Europoort (2 ha) and a small spontaneously developed brackish marsh with a size of 3 ha in the lee of a landing pier opposite the town of Maassluis. This polluted brackish marsh, often partly covered by waste, is the only remnant of the brackish soft vegetated intertidal ecotopes of the Rhine-Meuse estuary, less than one thousandth of the area they covered around 1950. The Brielsche Maas was closed by a dam on the sea side

in 1950 to shorten the coastline, and in 1953 the Botlek was also dammed, turning the Brielsche Maas into a freshwater lake. An entire estuary with a transition zone from salt to fresh water conditions had thereby disappeared. The “De Beer” nature reserve was sacrificed to the development of Europoort and the Maasvlakte, thus demolishing one of the most precious nature reserves of Western Europe. It was Europe’s largest dynamic dune area and one of the most important breeding grounds for many seabirds of the North Sea (Van Beusekom et al., 1930). Of the Brielsche Maas water system, only part of the Oude Maas remains. The shores of this tidal river section are mainly covered by debris (6 ha).

In 2008, the 6598 ha estuarine area consisted of tidal harbours (65%), tidal rivers (35%), hard substrate intertidal ecotopes (5%) and soft substrate intertidal ecotopes (0.3%). Although there were artificial beaches and dunes on the seaward side of the artificial Maasvlakte plain, and tidal flats and salt marshes in the southern part of the plain, they were not in direct contact with the remains of the Rhine-Meuse estuary and not considered to be part of it.

The Delta Works project considerably changed the hydrology of the Rotterdam harbour area. The hydrology of the area is nowadays strongly controlled by the drainage regime of 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 river water. To avoid salinization via the deepened Scheur/Nieuwe Waterweg waterways upstream of Rotterdam, an amount of 1500 $m^3 s^{-1}$ of river water is directed to the Rotterdam harbour area, i.e. the Scheur and Nieuwe Waterweg (1300 $m^3 s^{-1}$) and Hartelkanaal (200 $m^3 s^{-1}$). This flow of fresh water via the Rotterdam harbour area can be maintained at a Qbr of 1700 $m^3 s^{-1}$ to 4500 $m^3 s^{-1}$. Below 1700 $m^3 s^{-1}$, the salinity gradient shifts inland, while above 4500 $m^3 s^{-1}$ it shifts seawards. At a Qbr of approximately 1100 $m^3 s^{-1}$, the Haringvliet sluices are closed completely and a mixture of Meuse and Rhine water flows into the sea at Hook of Holland.

Petrifying the estuary

Table 2 serves as a guideline for the following paragraphs about the petrification of the estuary. Before the appearance of the shipworm (*Teredo navalis*) in 1730 (Sellius, 1733) dikes or shores were not protected by stones. The massive destruction of wooden protecting structures in 1731 and 1732 (Vrolik et al., 1860) triggered the hardening of large parts of the Dutch coastline. Later outbreaks of the shipworm in the 18th and 19th centuries infected sluices and dolphins, and its boring activity led to harbour quays collapsing. The use of

stone for shore and dike protection, for quays and in hydraulic engineering became common practice.
Around 1835, the area of hard substrate intertidal ecotopes was still limited and mainly consisted of the quays of the Rotterdam harbours (Fig. 7). Even then, however, the length of the hard shores along the Nieuwe Maas already exceeded its length by more than a factor of 2. Further stretches of hard intertidal substrate were found as quays along the river Nieuwe Maas, as a few small training walls and as reinforcements of the outlet of drainage sluices. The soft shoreline along the estuary exceeded the length of the rivers by a factor of 14. On average, there were 80 ha of soft substrate intertidal ecotopes per km of river, with a maximum of 109 ha per km along the Brielsche Maas water system.
Despite the many regulatory works and a significant expansion of the hard intertidal shore due to harbour extensions between 1835 and 1880, the length of the soft shoreline along the estuary increased slightly. The average area covered by soft substrate intertidal ecotopes, however, declined by 50% to 40 ha per km of river. Further river training of the Nieuwe Maas doubled its hard shores to a length of some 30 km, but due to the many small creeks within rush and reed beds and tidal willow coppice, the soft shoreline decreased only slightly. The total length of the hard river shoreline tripled, while the hard shoreline along the harbours almost doubled compared with 1835, especially along the Nieuwe Maas.
The harbour area along the Nieuwe Maas grew by a factor of almost 10 between 1880 and 1935, leading to a hard shore along the river and harbours stretching for 101 km, or about seven times the length of the river. The soft shoreline of the river decreased by a factor of 10, to less than twice the length of the river. Although 15 km of soft harbour shoreline existed when the aerial photographs for the maps were taken in 1934, this was only a temporary situation, with harbours under construction at that time. Between 1880 and 1934, the Scheur and Nieuwe Waterweg waterways had undergone a complete metamorphosis. Large parts of the soft shores had been straightened and protected by packed stone revetments, while old groynes had been enlarged and many new ones built. The hard shoreline grew to 56 km, more than twice the length of the river and 3.5 times the total length of the soft shoreline, which was reduced by 93% in the same period. Along the Brielsche Maas water system on the other hand, sedimentation in the Maasmond and the formation of new reed and rush beds with many small creeks meant that the soft shoreline grew by 50% to 629 km, 11 times the length of the water system itself. The closure of the Brielsche Maas and the exponential harbour expansion along the Scheur/Nieuwe Waterweg between 1950 and 1970 caused the almost complete disappearance of soft substrate intertidal ecotopes. In 2008, only a few hundred metres of soft

shoreline at low tide were present in front of the stone revetment of the dikes and between the groynes. With a total of 344 km of hard shoreline, the estuary contours were fixed and completely petrified.

Figure 8 Aerial view in July 2012 of the genesis of Maasvlakte 2 (left from black line). The line indicates the border between Maasvlakte 1 (right) and Maasvlakte 2 (left)(see Fig. 1). Photograph by Aeroview, Rotterdam, the Netherlands.

Estuarine developments and perspectives

Recent developments and perspectives for the Rhine-Meuse estuary

The construction of the second Maasvlakte plain started in September 2008. This is a seaward extension of the Rotterdam harbour area (Fig. 8), covering about 2000 ha, expanding the wet harbour area by another 510 ha and the hard substrate by 22 km of quay wall, creating another 6.6 ha of hard substrate intertidal zone. Completion is expected in the course of 2013/2014. To compensate for the loss of part of the seabed, a 25,000 ha area of the North Sea south of the Maasvlakte has been designated as a marine reserve. In addition, a new 35 ha dune area is being created north of Hook of Holland (Project Organisatie Maasvlakte 2, 2008). The current infrastructure of rivers, harbours, industrial and urbanized areas hampers large-scale restoration of soft estuarine ecotopes by removal of hard substrate, landward coastal realignment or managed retreat. Only in some small lee sites in the harbour area, kilometres apart, could some brackish marshes and reed and rush beds, covering a few ha, be created by sediment supplementation (Paalvast, 1998, Stikvoort et al., 2002). However, more and more ports along the river Nieuwe Maas are losing their trade, as the size of container ships and bulk carriers continues to increase and the new handling facilities and infrastructure on the first and second Maasvlakte plains are adapted to this. This creates opportunities to restore freshwater soft estuarine ecotopes in the near future in the upstream harbours, and the City of Rotterdam has made proposals to do so on a small scale in their new area development plans for old harbours.

On the 2nd of October 2013 the Port of Rotterdam, Rijkswaterstaat, the City of Rotterdam and the World Wildlife Fund signed an agreement to develop over a period of 10 years a nature–friendly intertidal zone along the south bank of the Nieuwe Waterweg with a length of 5 km. Within this zone a brackish vegetation and intertidal sand and mud flat of some 20 ha will develop over time. This is only 0.4 percent of the 4745 ha of soft estuarine intertidal ecotopes that existed in the Noordrand around 1835, but it might be a first step towards ecological restoration in this part of the Rhine-Meuse estuary. The return of soft estuarine ecotopes along the salinity gradient of the Rhine-Meuse estuary can be achieved by changing the drainage regime of the Haringvliet sluices (Smit et al., 1997, Paalvast et al., 1998, Storm et al., 2005), viz. by opening the sluices not only around low water slack tide but also at high tide. The construction of the Haringvliet sluices allows them to be used as a storm surge barrier. Furthermore, large parts of the former estuarine infrastructure are still intact, and habitat development projects that have been carried out in the last two decades have all taken a new management of the sluices with a return of estuarine dynamics into account. However the reintroduction of estuarine dynamics in the Haringvliet inlet will not lead to the same situation as before the closure of the Delta inlets. The Haringvliet sluices not only prevent the return of the old tidal regime, but also have a great impact on sediment transport to and from the Haringvliet. For example, the sill of the sluices (8 m above the sea floor) prevents the transport of coarse sand from the sea to the Haringvliet (Van Wijngaarden and Ludikhuize, 1997).

If it should be decided not to change the management of the Haringvliet sluices by opening them at flood tide to restore estuarine dynamics, this would not only hamper the development of soft estuarine ecotopes (Paalvast et al., 1998), it would also have consequences for a number of estuarine ecosystem services (see Barbier et al., 2011). A few examples are given.

Erosion control would require the maintenance of foreshore protection by means of riprap to avoid further erosion of the banks towards the dikes as result of the disappearance of the tide.

Some migratory fish, such as Salmon (*Salmo salar*) and Sea Trout (*S. trutta*), are able to enter the Haringvliet when the sluices are open at ebb tide as river water is being discharged, but they are not able to reach their upstream spawning grounds in the river Rhine and Meuse via the Haringvliet at discharges below 1500 m^3, as the sluices are then also closed at ebb tide (Hop et al., 2011). Estuarine residents such as Smelt (*Osmerus eperlanus*), Flounder (*Platichthys flesus*) and Twaite Shad (*Alosa fallax*) are currently unable to build up viable populations in the Haringvliet (Van Leeuwen et al., 2004), while catadromous fish species like Flounder (*Platichthys flesus*) and Eel (*Anguilla anguilla*) are unable to migrate upstream as the transport of their larvae towards fresh water depends on the tidal currents. Conversely, freshwater fish are being washed out to sea in large quantities (up to 10,000 kg per day) at ebb tide at high river discharges, and are unable to return to the Haringvliet at high tide, so they die in the salt water (Hop et al., 2011). The former function of the Haringvliet estuary as a nursery for Plaice (*Pleuronectes platessa*), Sole (*Solea solea*) and Herring (*Clupea harengus*) would not be restored either if the sluice regimen is not changed (Paalvast et al., 1998a).

A return of estuarine dynamics with its gradient from fresh to saline conditions would stimulate recreation and tourism by enhancing the amenity value of the landscape, as it leads to an ever changing landscape, in which the intertidal zone of marshes, reed, rushes, sand and mud flats plays an important role. Waterbound recreation would also benefit as more dynamics means more challenges, while anglers would greatly benefit from the increased fish biodiversity (Paalvast et al., 1998b).

An important aspect is to secure a sufficient minimum supply of fresh water. The return of estuarine dynamics would mean that part of the Haringvliet would have a salinity gradient going from mesohaline to fresh (Bol and Kraak, 1998). This would have consequences for both the intake of drinking water (Meeuwissen and Brink, 1998) and the supply of water for agriculture (Anonymous, 1998). Moreover water intake points would have to be relocated.

In 1989 the Third National Policy Document on Water Management (NW3) was published by the Dutch Government (Ministerie van Verkeer en Waterstaat, 1989), with ecological restoration of the Dutch water systems one of the main issues. It was a turning point in Dutch water management, as it sets out a new strategy under the name of “Integrated Water Management”. The strategy proved to be a success, and the Fourth National Policy Document on Water Management (NW4) issued in 1998 retains the same approach (Ministerie van

Verkeer en Waterstaat, 1998). In 2007, the Dutch government created the Delta Commission II (DC II), which is charged with investigating ways to strengthen the water defence system and the infrastructure of the country in order to be well prepared for the expected climate change, in both a physical and governance sense. In particular, the commission was requested to produce an integral vision for the coming centuries. As regards the safety of the Rijnmond area, DC II proposed a scenario of closable open systems with weirs in conjunction with using the Haringvliet sluices as a storm surge barrier (Deltacommissie 2008, 2008).

In 2009, the National Water Plan (NWP) was presented, as a follow-up to NW4 (Stumpe, 2009). One of the policy choices in both the NW4 and NWP was the restoration of estuarine dynamics by eliminating the strict separation between the various basins in a controlled manner. The implementation of a new management scheme for the Haringvliet sluices with a new drainage regime involving partial opening of the sluices at high tide at Rhine discharges of 1500 m^3 or higher (the Kierbesluit, literally the decision to set the sluices ajar), which was planned for 2010 (Kerkhofs et al., 2005, Rijkswaterstaat, 2009), would have been a first step towards the estuarine recovery of the Haringvliet, Hollandsch Diep and Biesbosch areas. The Dutch government, however, decided soon after it came into office in 2010 not to discuss and implement the plan, though it later reversed its decision after pressure from the EU. At the same time, it was decided that a new drainage regime would be the final change in the management of the Haringvliet sluices. The implementation of the Kierbesluit is now foreseen for mid-2018 and is a separate decision that does not prelude a further recovery of the estuarine dynamics (Staf Deltacommissaris, 2013) This implies that it is not very likely that the near future will see a recovery of estuarine dynamics and hence of soft estuarine ecotopes within the Rhine-Meuse estuary. This policy is at odds with NWP and the recommendations of DC II, and contrasts with the development of estuarine restoration elsewhere in Europe (Attrill, 1998, Dauvin, 2006, Antheunisse and Verhoeven, 2006, Ducrotoy and Dauvin, 2008, Ducrotoy, 2010).

The restoration of estuarine dynamics may however get a boost from a completely different side, that of safety. The current drainage regime of the Haringvliet sluices leads to high water velocities in the Spui, Dordtse Kil and Oude Maas river branches (Fig. 1) with severe erosion along the whole channel, which will in the long run undermine the stability of the dikes. A solution to the problem can be generated by managing the Haringvliet sluices as a storm surge barrier (Anonymous, 2012). The Dutch division of the Word Wild Life Fund has launched a new proposal for a safer and more attractive South-West Delta area. It comprises the reopening of the sea inlets such as the Haringvliet by removing the barriers, and building climate-proof dikes in combination with the creation of natural wetlands. In case of storm surges the hinterland could be protected with a new generation of barriers that do not hamper the free transport of sediment, tides and animals (Braakhekke et al., 2008, Van Winden et al., 2010). A pilot study conducted by Böhnke-Henrichs and De Groot (2010) shows an increase in Total Economic Value (TEV) of at least 500 million Euro per year (from a TEV of 1.26 billion currently to 1.74 billion under the open Haringvliet scenario) based on 30 ecosystem services and subservices that were included in the analysis (the costs for removing barriers and building new dikes were not included in the analysis).

Wider perspectives and developments elsewhere

The losses of pristine estuarine ecotopes and the expansion of hard substrate ecotopes are not confined to the Rhine-Meuse estuary. Since the majority of large harbours in Western Europe have developed over centuries and are situated as far inland along the estuary as ancient ships could sail, they are characterized by developments comparable to those in the south-western part of the Netherlands. Examples are Hamburg on the Elbe, Bremen on the Weser, Emden and Delfzijl on the Ems, Antwerp on the Western Scheldt, London on the Thames, Hull on the Humber, Rouen on the Seine, Nantes on the Loire, Bordeaux on the Garonne and Lisbon on the Tagus. Over the last two centuries, these estuaries have undergone great hydromorphological changes (increased tidal range, salt intrusion further upstream, going from multichannel to single-channel) as a result of dredging to provide greater depth for shipping, land reclamation for agriculture, urbanization and industrialization and port development. In estuaries such as the Elbe (Reky, 1992, Fickert and Strotmann, 2007), Ems (Herrling and Niemeyer, 2008) and Seine (Bessineton, 1997, Lesueur and Lesourd, 1999,) most marshes have been turned into polders, while large parts of marshes and sand and mud flats have disappeared by coastal squeeze due to hydrological changes caused by dredging and river training. One of the most extreme examples is the Ems estuary (De Jonge et al., 2014) where a combination of channel maintenance dredging in the lower estuary and river deepening in the upper estuary (tidal Ems river) has led to significantly increased concentrations of suspended material. In the main estuary, the concentrations have increased 2- to 3-fold, while in the river, the concentrations have increased by an order of magnitude. As a result, the main estuary suffers from low primary production. The tidal Ems river is now characterized by extremely high suspended matter concentrations and extremely low oxygen values over a distance of about 15 to 25 km during summer, so organisms cannot migrate between fresh water and sea water and vice versa. The Humber estuarine area has been reduced over time by human activities from over 90,000 ha to about 30,000 ha, and some 50% of the original intertidal zone area has been sacrificed to such activities (Jones, 1988, Winn et al., 2003). In the same time, shorelines have been straightened and protected by a variety of hard materials. Large parts of the shoreline of the river Seine, from the mouth of the estuary up to Rouen and even further upstream, consist of concrete, steel, asphalt, riprap, debris etc. (personal observations for GIP Seine-Aval), while half of the entire river length of the Elbe estuary is protected by embankments (Anonymous, 2010). The loss of large parts of the intertidal zone and the hardening of the shores has undoubtedly lowered biological productivity in estuaries to a great extent.

In Europe, the restoration/rehabilitation of estuarine ecotopes and the management of estuaries has been mainly a national or regional issue. Between 2004 and 2008, the HARBASINS project, part of the Interreg IIIB North Sea Programme, was carried out with the aim of enhancing the compatibility of management strategies and international cooperation for the North Sea's coastal waters, estuaries and river basins. Its focus has been on harmonizing the EU Water Framework Directive and international cooperation for integrated management of estuaries and coastal waters in the North Sea Region, ultimately leading to ecosystem restoration and instruments that are compatible which sound environmental management of interconnected coastal zones in the North Sea (Enserink et al., 2007). As a follow–up, the Tide project started in 2010, with the aim of finding multi-beneficial solutions for future sustainable estuary development (Anonymous, 2010a). So far, however, no concrete measures have been taken. For the Ems estuary, Schuttelaars et al. (2013) have proposed a management solution to solve the problem of the high suspended matter concentrations in the tidal Ems river by removing the weir at Herbrum. If this plan is implemented, the river will be lengthened by 7 km, which is enough to significantly change the hydraulics so that the accumulation of suspended matter will no longer take place in that part of the system, but will return more or less to its original position (near Emden).

The estuarine ecosystem would be best served in the near future if port activities were moved from inland locations to the mouths of the estuaries. This should lead to a decrease in the pressure on the estuarine ecosystem, as dredging for greater waterway depths, with all its consequences, would no longer be necessary. In this respect, the development of the second Maasvlakte could set an example for port development elsewhere. Nevertheless, we need to be aware of unforeseen effects of engineering on and along the coast, as has been illustrated by De Jonge and De Jong (1992). They showed that the effects of the dumping of dredge sludge at the Dutch coast near Scheveningen clearly affected the suspended matter concentrations in the western Dutch Wadden Sea, 120 to 180 km further north.

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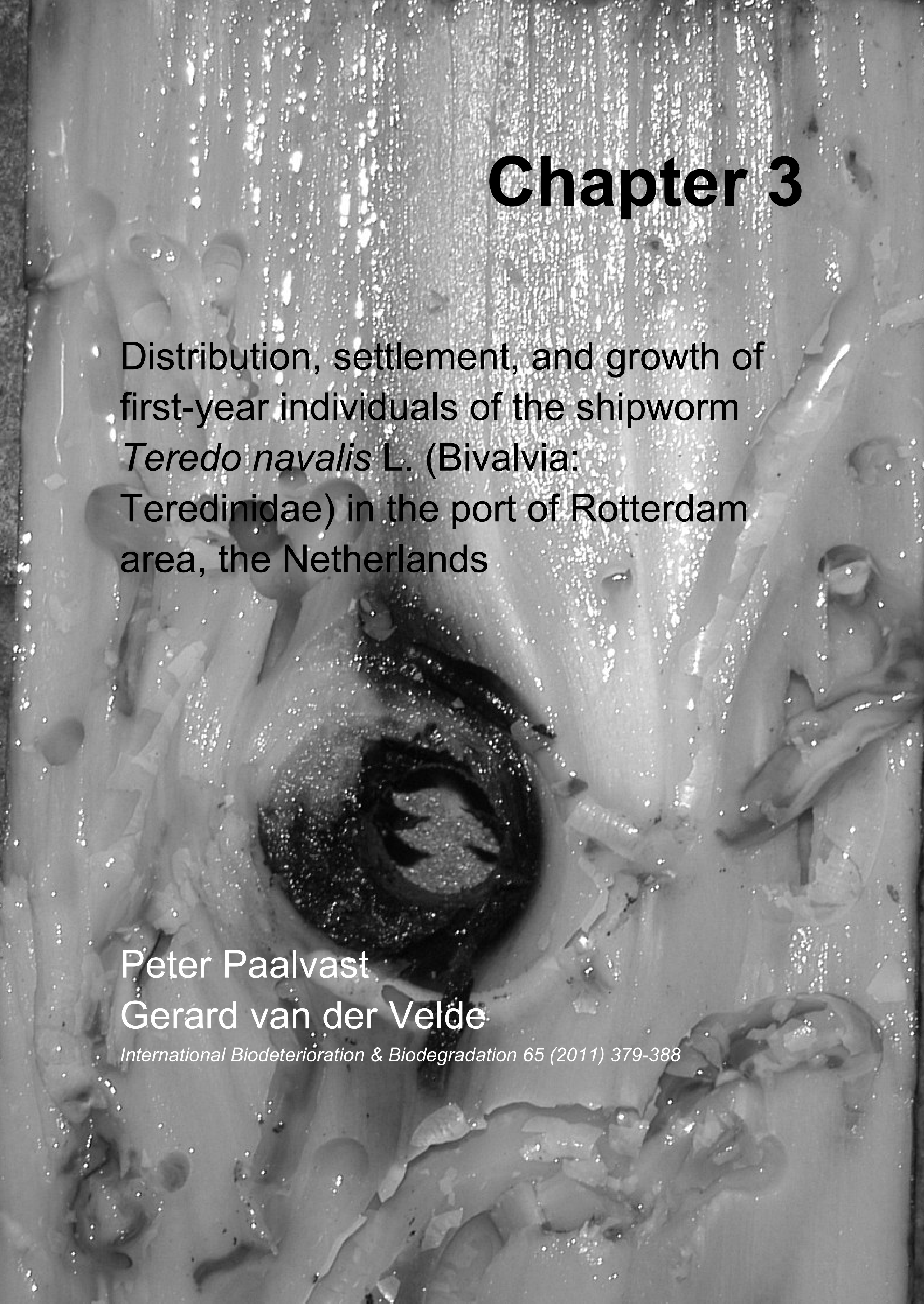

Chapter 3

Distribution, settlement, and growth of first-year individuals of the shipworm *Teredo navalis* L. (Bivalvia: Teredinidae) in the port of Rotterdam area, the Netherlands

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Abstract

During the period 2004 -2008 the distribution, settlement and growth of first year shipworms (*Teredo navalis* L., 1758.) was studied by exposing fir and oak panels in the port of Rotterdam area, which is situated in the Rhine-Meuse estuary in the Netherlands and covers the complete salinity gradient. Shipworms were found yearly in the western large polyhaline harbours. On only a few occasions they were found in harbours that showed large seasonal and daily fluctuations in salinity over the years. In 2006 the shipworm was found in fir panels 20 km upstream from the polyhaline harbours, demonstrating their ability to travel with the tidal currents over considerable distances and to settle once the abiotic conditions become favourable. Although the water temperatures allowed them to breed from April till November, infestations were not found before September and from the size of the animals in the panels it was concluded that in the port of Rotterdam area they spawned from August until the end of November.

The settlement height was negatively correlated with the distance of the panels to the sea floor. In the first season after settlement they showed a substantial growth rate of 0.18 cm day^{-1} in 2006. The longest shipworm found was in 2006 and measured 36.8 cm after 4 – 5 months of growth after settlement. Infestations and growth were lower in oak than in fir wood. In 2006 the maximum loss of wood caused by individuals settled in the same year in panels at the bottom accounted 12.4%. Shell size and body length of the animal after the first season of growth showed a significant positive logarithmic relation. In both 2006 and 2007 a similar relation between the average boring tube diameter and the length of the animals was found.

Lower river discharges leading to salinisation of the eastern part of the port of Rotterdam area create conditions favourable for the shipworm with serious consequences for the condition of the piles where the quays are built upon.

Introduction

Shipworms are ‘xylophagous’ marine bivalve molluscs belonging to the Teredinidae which are specialized to bore into wood. The first documented mass appearance of the shipworm (*Teredo navalis* L.) in the coastal waters of the Netherlands took place in 1730,1731, and 1732 and led to massive destruction of the wooden constructions that protected the dikes in Zealand and Westfrisland (Vrolik et al., 1860). Later outbreaks of the species occurred in 1770, 1827, 1858 and 1859. Also sluices and dolphins in harbours upstream the Rhine-Meuse estuary were found to be infected in 1826. The conclusion was drawn that several seasons of low river discharges resulting in increased salinity had created favourable conditions for the shipworm to settle and survive in the area. The shipworm commonly occurs in the Dutch coastal waters and the enclosed salt water bodies in the Dutch Delta Area (Van Benthem Jutting, 1943, De Bruyne, 1994).

The adult shipworm tolerates salinity conditions between 5 and 35 (Nair and Sarawathy, 1971) making the mouth of estuaries with daily changing salinities a hospitable habitat for this species. The animal thrives and reproduces at salinities of 10 and higher (Soldatova, 1961 in Tuente, 2002). Below a salinity of 9-10 boring activity stops (Blum, 1922). The pelagic larvae survive at salinities as low as 5 (Hoagland, 1986). The optimal water temperature for growth and reproduction lies between 15˚C and 25˚C. Spawning starts when the temperature rises above 11 to 12˚C and the animals may breed from May until October (Grave, 1928). Temperatures up to 30˚C are tolerated. Below 10˚C the boring activity drops and it stops at 5˚C. At temperatures around the freezing point they will hibernate until the water temperature becomes favourable again.

The port of Rotterdam covers the complete salinity gradient of the Rhine-Meuse estuary. The large harbours in the western part are always polyhaline and the shipworm could settle if wooden constructions to bore into are present. The bottom water of the harbours of the eastern part is fresh to oligohaline at average river discharge, but at discharges below 1000 $m^3 s^{-1}$ the area becomes α-mesohaline with salinities over 10. If the discharge of the river Rhine remains below 1000 $m^3 s^{-1}$ during the breeding season for a few weeks the conditions might become favourable for the shipworm. Larvae transported with the tidal currents to the eastern part of the port of Rotterdam area could perhaps settle and grow in the oak and pine on which several old quays are built upon. 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. In September 2003 the Port Authority decided to test the validity of the above hypotheses and sets of fir panels where placed at the bottom at various sites of the port of Rotterdam area yearly from 2004 till 2008 and were inspected for the presence of shipworms .

The following research questions were formulated:

1. What is the distribution of the shipworm related to salinity and what is the potential and actual breeding season and length of boring period of *T. navalis* in the port of Rotterdam area based on water temperature and settlement on fir panels, respectively?
2. Is it possible for the shipworm to settle in the eastern part of the port of Rotterdam area at low river discharges and is settlement equally distributed over the water column or is there a relation with water depth?
3. How fast does the shipworm grow in fir wood the first season after settlement, how much wood loss they cause in that period and is there a difference in settlement and growth of shipworms in fir and oak panels?
4. Can shell size be used to estimate the length of the shipworm and its cause of wood loss and is there a relation between the length of the shipworm and its average boring tube diameter?

Materials and methods

Study area

The port of Rotterdam is situated in the estuary of the rivers Rhine and Meuse (Fig. 1A). It stretches over a length of 40 km and covers 10,500 hectares of which 3440 hectares of the area is water of harbours and 1960 hectares rivers and canals. Under average conditions, at a river Rhine discharge (Qbr) of 2200 $m^3 s^{-1}$ at the Dutch-German border, 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 regime of the Haringvliet sluices (Fig. 1A), based on the discharge of the Rhine at the Dutch-German border. The degree to which the sluice gates are opened at ebbtide increase with increasing discharge of fresh water. To avoid salinisation upstream of Rotterdam an amount of 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 moves land inward, 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 water flows in the sea at Hoek van Holland. The isohalines of the bottom water in the area under average and low river discharge (1000 $m^3 s^{-1}$)

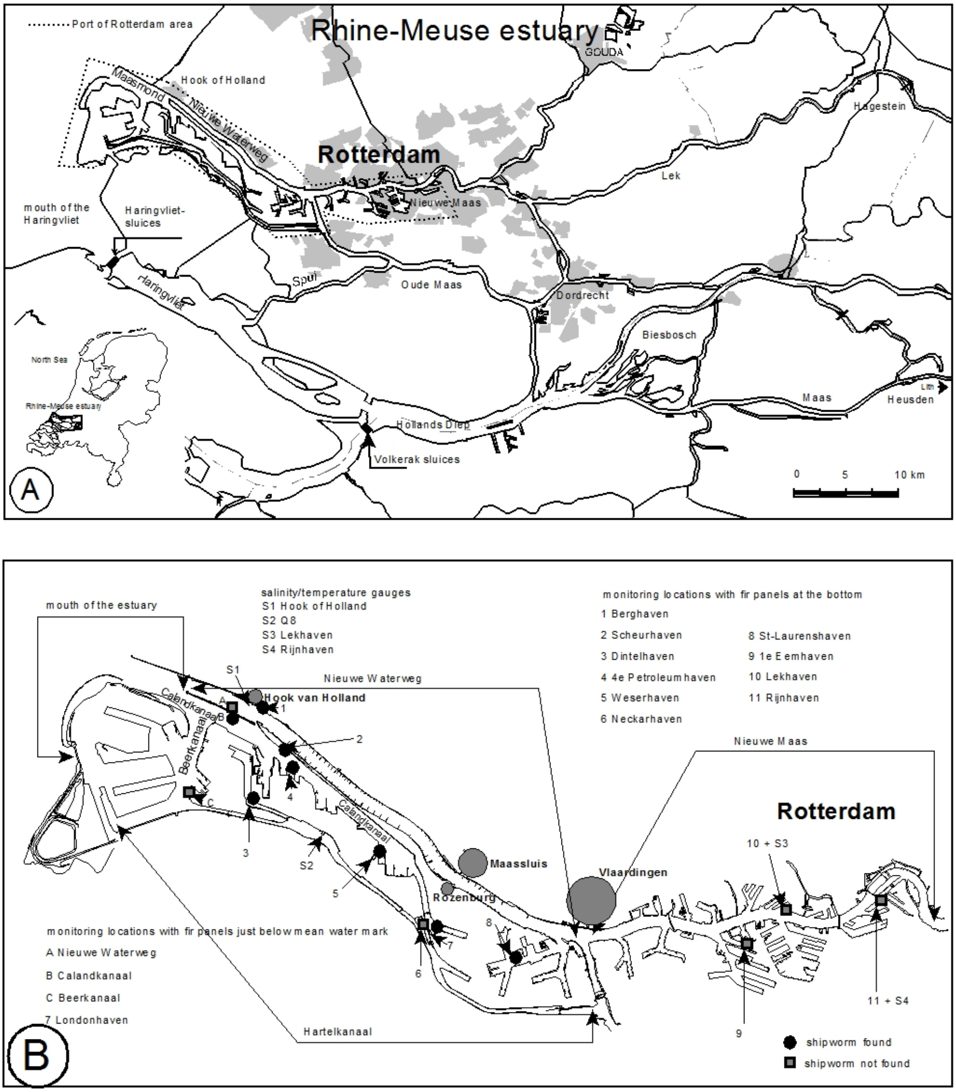

Figure 1 A. The port of Rotterdam in the Rhine-Meuse estuary. B. Monitoring locations and salinity/temperature gauges in the Port of Rotterdam area and the presence (black dots) and the absence (grey squares) of the shipworm in the monitoring panels during the period 2004 - 2008.

were calculated by the model RIJNAMO of Rijkswaterstaat (Bol and Kraak, 1998) (Fig. 2A, 2B).

The Rhine-Meuse estuary is microtidal with an average tidal range of 1.75 m at Hoek van Holland gradually decreases upstream till 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 period of flood, a 4-h period of ebb and a 4.5-h low-water period.

Salinity, oxygen and temperature measurements

Salinity and temperature were recorded every 10 min at four stations (Fig. 1B). The water depth given is in metres related to NAP (Normaal Amsterdams Peil or Amsterdam Ordnance Datum). NAP is a vertical datum in use in a large part of Western Europe and is close to the mean sea level at the Dutch coast. In 2003 salinity depth files with 1-m intervals from surface to bottom (i.e., sea floor) were obtained with a WTW-conductivity meter (Cond 3301) with a TetraCon®325 conductivity and temperature sensor.

To determine if oxygen was a limiting factor for the shipworm from October 2004 till November 2005 monthly samples of the bottom water at eight locations were taken and the concentration was measured with a HQ20 Hach Portable LDOTM dissolved oxygen/pH meter.

Sampling

The distribution of the shipworm by its settlement was investigated by placing fir (monitoring) panels at the bottom or just below the mean water mark at different locations (Fig. 1B) along the salinity gradient. The vertical panels measured 10 x 20 x 2 cm. Five locations were in use from 2004 to 2008, seven from 2004 to 2007 and six from 2005 to 2008. In 2006 the number of locations was extended to 16, but at three locations the fir panels disappeared and were not used in the analysis, leading to 13 locations from which information about the shipworm could be obtained (Table 1).

The settlement season was studied by retrieving fir panels monthly in 2004 from August to December and in 2005 from July to December. A set of oak panels of 10 x 20 x 2 cm was placed next to the fir panels in 2006 in the Scheurhaven to compare settlement and growth in both types of wood (Table 1).

The settlement height in relation to the distance to the bottom (sea floor) was studied in 2006 by placing a construction (Fig. 3) with fir panels with a distance from the bottom of 0, 25, 50, 75 and 100 cm at the bottom of the Scheurhaven. Panels were retrieved in July, October and December 2006. In 2007 this was repeated at the same station but with four beams, with a length of 540 cm, a

Table 1 Monitoring locations in the period 2004 – 2008 with the dates of exposure (exp) and retrieval (retr) and the number of panels exposed and retrieved. 12* = oak panels, dis = disappeared.

	monitoring year																						
	2004						2005							2006				2007				2008	
location\dates	exp	retr	retr	retr	retr	retr	exp	retr	retr	retr	retr	retr	retr	exp	retr	retr	retr	exp	retr	retr	retr	exp	retr
01 Berghaven -5 m NAP	8-6	20-8	19-9	4-11	26-11	10-12	10-3	5-7	6-8	3-9	3-10	2-11	11-12	3-4	27-7	3-10	10-12	2-4	24-7	10-10	4-1-08	16-4	21-1-09
02 Scheurhaven -5 m NAP	8-6	20-8	19-9	4-11	26-11	10-12	9-3	8-7	9-8	5-9	5-10	3-11	16-12	4-4	27-7	3-10	10-12	2-4	24-7	10-10	4-1-08	16-4	21-1-09
03 Dintelhaven -4 m NAP							9-3	8-7	9-8	5-9	5-10	3-11	16-12	6-4	27-7	3-10	10-12	2-4	24-7	10-10	4-1-08	16-4	21-1-09
04 4e Petroleumhaven -3 m NAP														6-4			10-12						
05 Weserhaven -3 m NAP														4-4			10-12						
06 Neckarhaven -4 m NAP							9-3	8-7	9-8	5-9	5-10	3-11	16-12	5-4	27-7	3-10	10-12	2-4	24-7	10-10	4-1-08	16-4	21-1-09
07 Londonhaven -1.5 m NAP							9-3	8-7	9-8	5-9	5-10	3-11	16-12	5-4	27-7	3-10	10-12	2-4	24-7	10-10	4-1-08		
08 St-Laurenshaven -9 m NAP	8-6	20-8	19-9	4-11	26-11	10-12	9-3	8-7	9-8	5-9	5-10	3-11	16-12	4-4	27-7	3-10	10-12	2-4	24-7	10-10	4-1-08	16-4	21-1-09
09 1e Eemhaven -3 m NAP	8-6				26-11	10-12											10-12						
10 Lekhaven -9.5 m NAP	8-6	20-8	19-9	4-11	26-11	10-12	10-3	5-7	6-8	3-9	3-10	2-11	11-12	3-4			10-12	2-4	24-7	10-10	4-1-08	16-4	21-1-09
11 Rijnhaven -8.0 m NAP	8-6	20-8	19-9	4-11	26-11	10-12								3-4			10-12	2-4			dis		
A Nieuwe Waterweg mouth -0.8 m NAP														7-4			10-12						
B Calandkanaal mouth -0.8 m NAP														7-4			10-12						
C Beerkanaal -0.8 m NAP														6-4			10-12						
location\number of panels	exp	retr	retr	retr	retr	retr	exp	retr	retr	retr	retr	retr	retr	exp	retr	retr	retr	exp	retr	retr	retr	exp	retr
01 Berghaven -5 m NAP	6	1	1	1	1	1	16	2	2	2	2	2	2	18	6	6	6	12			12	12	12
02 Scheurhaven -5 m NAP	6	1	1	1	1	1	16	2	2	2	2	2	2	18	6	6	6	36+12*	12	12	12	12	12
04 Dintelhaven -4 m NAP							16	2	2	2	2	2	2	18	6	6	6	12			12	12	12
05 4e Petroleumhaven -3 m NAP														12			12						
06 Weserhaven -3 m NAP														12			12						
07 Neckarhaven -4 m NAP							16	2	2	2	2	2	2	18	6	6	6	36	12	12	12	12	12
08 Londonhaven -1.5 m NAP							16	2	2	2	2	2	2	18	6	6	6	12			12		
09 St-Laurenshaven -9 m NAP	6	1	1	1	1	1	16	2	2	2	2	2	2	18	6	6	6	36	12	12	12	12	12
10 1e Eemhaven -3 m NAP	6				1	1											4						
11 Lekhaven -9.5 m NAP	6	1	1	1	1	1	16	2	2	2	2	2	2	18	6	6	6	36	12	12	12	12	12
12 Rijnhaven -8.0 m NAP	6	1	1	1	1	1								18	6	6	6	12			dis		
A Nieuwe Waterweg mouth -0.8 m NAP														6			2						
B Calandkanaal mouth -0.8 m NAP														6			6						
C Beerkanaal -0.8 m NAP														12			12						

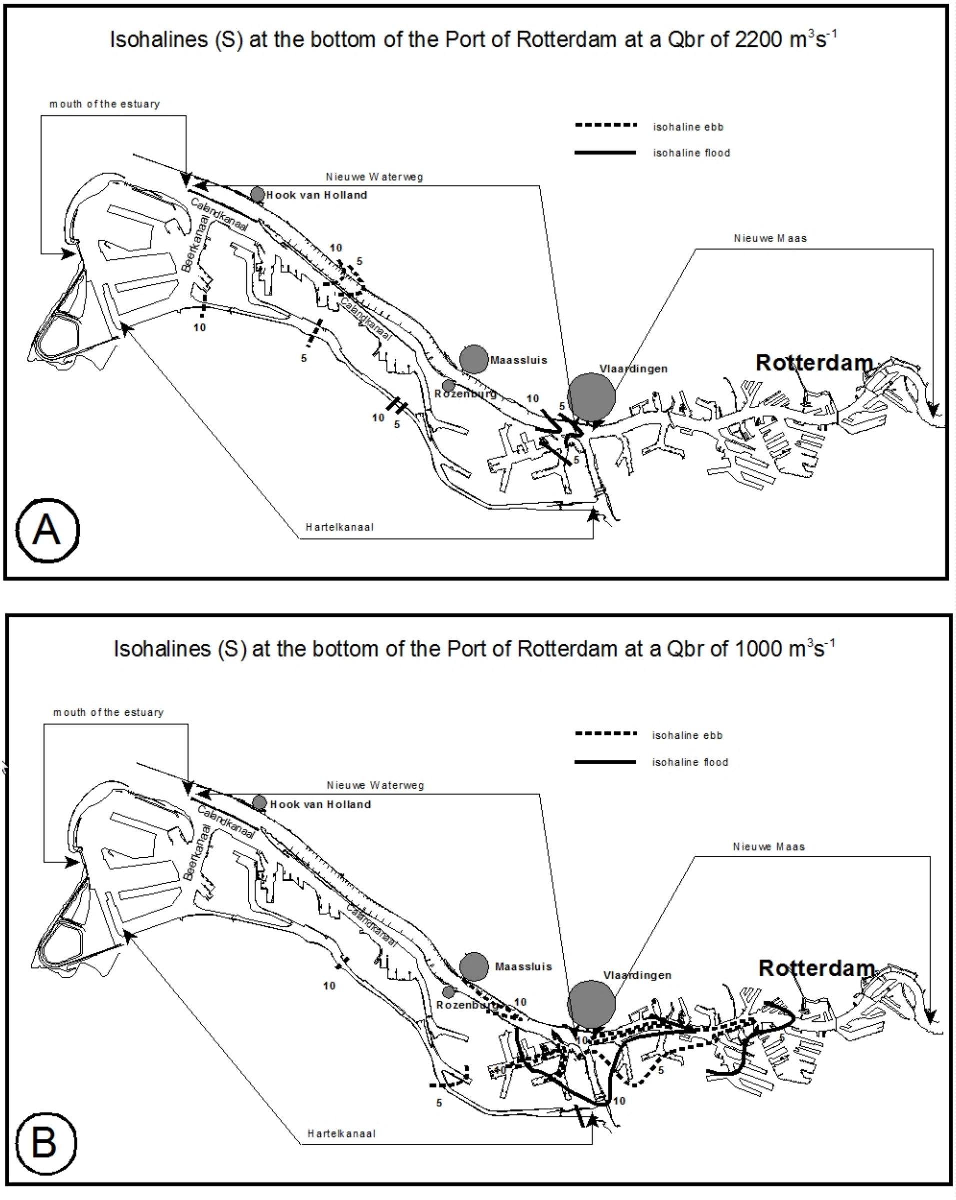

Figure 2 A. The isohalines 5 and 10 at ebb and flood in the port of Rotterdam area at an average discharge of the Rhine at the Dutch-German border (Qbr) of 2200 $m^3 s^{-1}$. B. The isohalines 5 and 10 at ebb and flood in the Port of Rotterdam area at a discharge of the Rhine at the Dutch-German border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

width of 10 cm and a thickness of 5 cm, covering the water column and intertidal zone. The beams were retrieved in January 2008 and sawed into pieces 20 cm long.

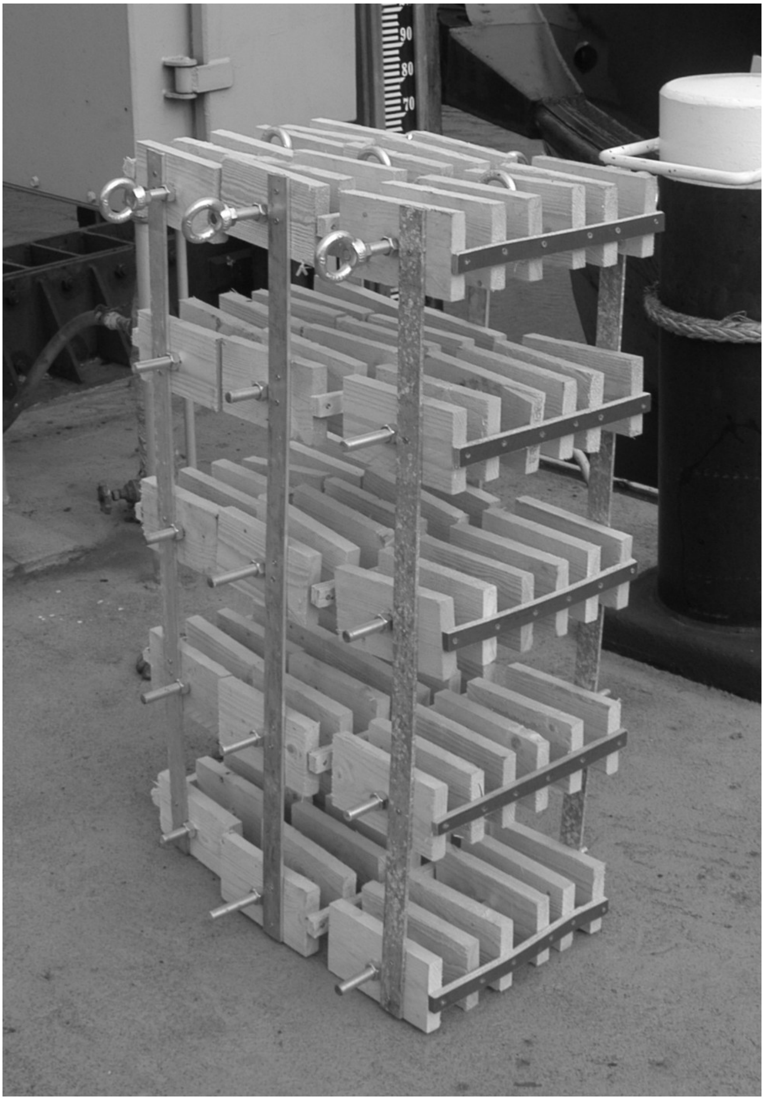

Figure 3 The construction with the fir panels to study the settlement height (0, 25, 50, 75 and 100 cm) in relation to the distance to the bottom placed in the Scheurhaven in 2006.

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Analysis

From the data of the measuring stations the daily minimum and maximum salinity was taken for a yearly overview of the salinity fluctuations in relation to the discharge of the river Rhine at the Dutch German border (Lobith; Bimmen). The mean daily water temperature was calculated.

Shipworm individuals were identified to the species level using the key in Hayward and Ryland (1995).

All panels and beam pieces were freed of fouling, placed in plastic bags, deep frozen if necessary and digitally radio graphed by Applus RTD Benelux. On screen the body length (length of the boreholes) and shell size was measured for each individual shipworm. Also, for the years 2006, 2007 and 2008 the average diameter of the boreholes was estimated, based on measurements of the diameter at 0.25, 0.50 and 0.75 of the length in order to calculate the loss of wood. Growth was calculated by comparing the average length of the shipworms in October with those in December in 2006 and 2007.

Statistical analysis was carried out with the aid of the computer program SPSS for Windows Release 11.0.0. The Levene's test for equality of variance and the independent t-test were applied for comparing the average length of the shipworms in 2006 and 2007. To compare the average length of the shipworms at the different monitoring locations and at different distances from the bottom the Levene's test for equality of variance and analysis of variance (One way Anova) were conducted. For testing the relation of settlement of shipworms and the distance to the bottom, the relation of body length and shell size, and the relation of body length and average boring tube diameter the curve fit and correlation coefficient were calculated and analysis of variance applied.

Results

Hydrography

The water temperature fluctuated between 3°C in winter and 25°C in summer in the Lekhaven and between 4 and 22°C at Hoek van Holland during 2004-2008. From April to November the water temperature was above 10°C, and it was above 15°C from June until mid-October. In spring and summer the river water temperature was higher than that of seawater, in autumn they were about the same, while in winter seawater temperature was higher. Over the period 2004-2008, out of 1814 days, for 1697 days the water temperature was high enough for the shipworm to exhibit boring activity. Spawning could have taken place in the period mid-April until mid-November.

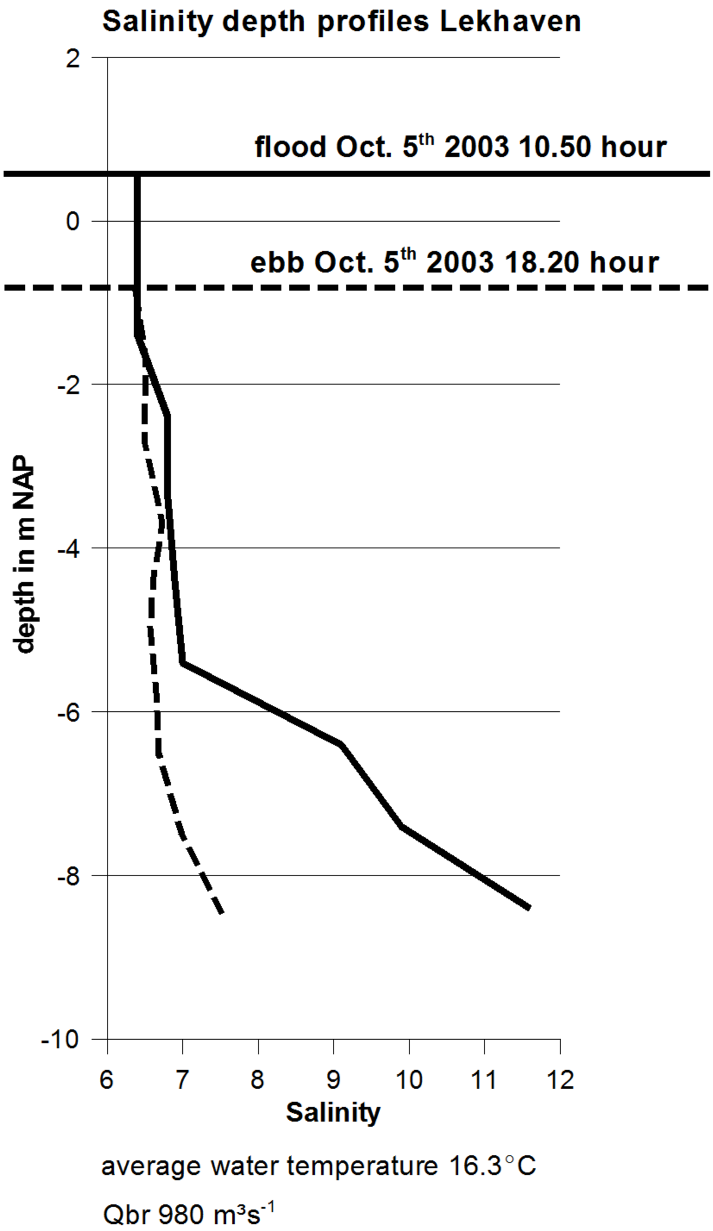

Figure 4 Salinity depth profiles of the Lekhaven in the eastern part of the port of Rotterdam area on Oct. 5, 2003.

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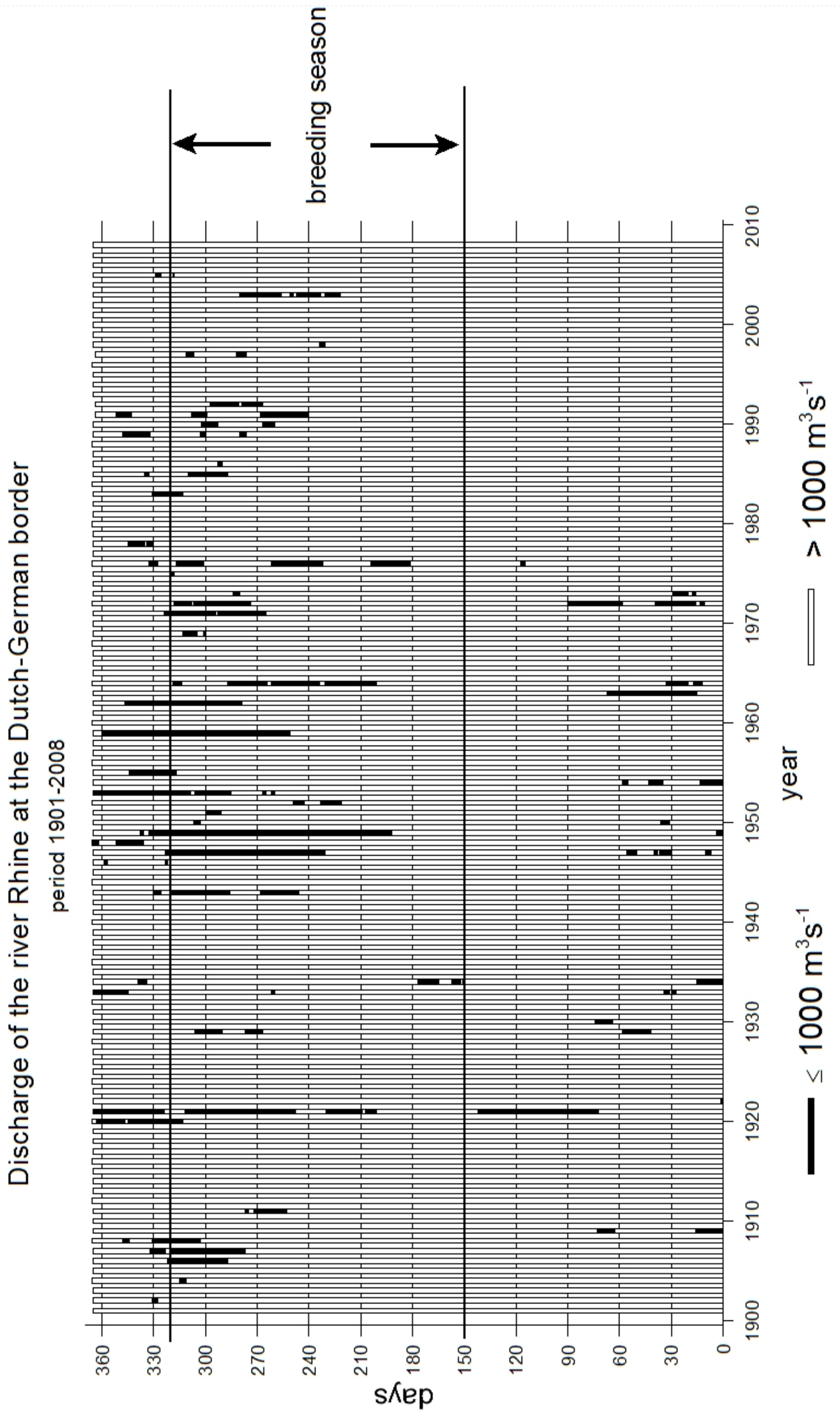

Figure 5 Discharges of the river Rhine at the Dutch-German border below and above 1000 $m^3 s^{-1}$ during the period 1901 and 2008 and their occurrence in the breeding season of the shipworm.

On Aug. 10, 2003 the Qbr (discharge of the river Rhine at the Dutch-German border) reached, approximately, the critical value of 1000 m^3 s^{-1}, with the consequence that in some eastern parts of the port of Rotterdam area the salinity reached values of over 10 and this situation lasted until Oct. 7, a period of almost two months.
Two salinity depth profiles were measured at flood and ebb on October 5, 2003 at a Qbr of 980 m^3 s^{-1} in the Lekhaven. The profile taken at flood demonstrates the stratification under conditions of high salt intrusion in this part of the port of Rotterdam area (Fig. 4). At these low discharges the conditions become favourable for the shipworm to settle.
In the period 2003-2008 in the eastern part of the port of Rotterdam area, salinity changed at the bottom several times from fresh-oligohaline to meso-haline conditions, but as the river discharge after 2003 until 2008 reached values below 1000 m^3 s^{-1} only for a few days, no suitable conditions for the shipworm occurred for settlement and growth. Long periods of discharges below 1000 m^3 s^{-1} occur (Fig. 5). In the last decade, in 15 separate years, there were periods of 30 days or longer then discharges below 1000 m^3 s^{-1} were recorded during the breeding season of the shipworm. The longest uninterrupted period with this critical discharge was in 1949, which had a duration of 141 days, but before 1970 the hydrology of the port of Rotterdam area differed greatly from the present situation because of the absence of the Haringvliet sluices and weirs in the Lek and Nederrijn.
In the western part of the port of Rotterdam area the waterways Hartelkanaal and Nieuwe Waterweg and adjacent harbours exhibited strong daily changes in salinity due to the tide and the river discharges. The large harbours Beer- en Calandkanaal where polyhaline throughout 2003-2008.
Oxygen levels measured between October 2004 and October 2005 at the monitoring locations were high and fluctuated between 80 and 120% saturation, with a median value of 98%. On only one occasion was an oxygen saturation level as low as 69% measured.

Distribution
The settlement of larvae as an indication of the distribution of the shipworm on the monitoring panels varied from year to year (Table 2).
The shipworm settled in the fir panels in the Scheurhaven throughout the monitoring period and in three individual years in those in the Berghaven. Only in 2006 were shipworms found in panels at other locations that were monitored from 2004 or 2005 until 2008, none of them, however, were in the eastern part of the port of Rotterdam area. In 2006 shipworms were also encountered in the

panels of the extra locations in the Calandkanaal, but not in those of the Beerkanaal (Fig. 1B).
Wooden piles made of Basralokus (*Dicorynia paraensis* Bentham) pulled out the polyhaline Calandkanaal contained many boreholes in the outer 5 cm. Inspection of fir piles from the harbours of Maassluis, Vlaardingen and the centre of Rotterdam did not show any damage caused by shipworms.
Examination of the shells of live animals in panels and beams and in empty burrows of the piles and driftwood from the Calandkanaal, showed that only one species, *T. navalis*, was involved.

Table 2 Number of shipworms that settled on 6 fir panels at the different monitoring locations in the Port of Rotterdam area during the period 2004 – 2008.
- = no shipworms found, blank = no panels at monitoring location.

Location\year	number of individuals per 6 fir panels				
	2004	2005	2006	2007	2008
01 Berghaven -5 m NAP	3.0	-	2.0	-	2.0
02 Scheurhaven -5 m NAP	24.0	9.0	74.0	40.0	3.0
03 Dintelhaven -4 m NAP		-	1.0	-	-
04 4e Petroleumhaven -3 m NAP			13.5		
05 Weserhaven -3 m NAP			23.5		
06 Neckarhaven -4 m NAP		-	-	-	-
07 Londonhaven -1.0 m NAP		-	8.0		
08 St-Laurenshaven -9 m NAP	-	-	14.0	-	-
09 1e Eemhaven -3 m NAP	-		-		
10 Lekhaven -9.5 m NAP	-	-	-	-	-
11 Rijnhaven -8.0 m NAP	-	-	-		
A Nieuwe Waterweg mouth -0.8 m NAP			-		
B Calandkanaal mouth -0.8 m NAP			19.0		
C Beerkanaal -0.8 m NAP			-		

Breeding season
Shipworms were never found in the panels before September. Small individuals with a body length of less than 50 mm were encountered in the panels from September to December, indicating a breeding season from August until the end of November.

Settlement in relation to the distance to the bottom
In both 2006 and 2007 the settlement of the shipworm was significant negatively correlated with the distance to the bottom (Fig. 6). Almost 75% of the shipworms were found in the first 60-cm and 80-cm water layer above the bottom in 2006 and 2007, respectively. In 2007, above 120 cm from the bottom shipworms were found only sporadically.

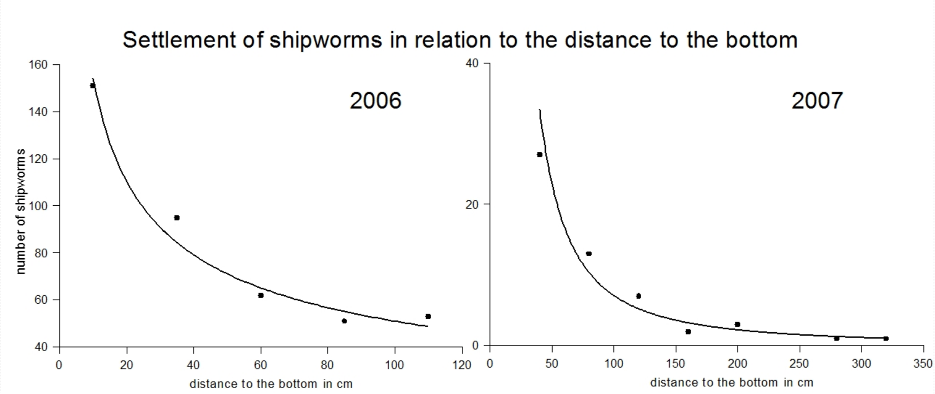

Figure 6 Settlement of shipworms in 2006 (left)($Y = 465X^{-0.48}$, $R^2 = 0.96$, $p < 0.003$) and 2007 (right) ($Y = 17028X^{-1.69}$, $R^2 = 0.94$, $p < 0.001$) in the Scheurhaven in relation to the distance to the bottom (sea floor).

Growth and wood loss

The number of shipworms found in the panels during 2006 and 2007 allowed calculation of body length frequency distribution, growth and caused wood loss. The body length frequency (Fig. 7) as a percentage of the total number of individuals in fir panels from the locations 2, 5, 7, 8 and B in the Calandkanaal (Fig. 1B), the polyhaline region of the port of Rotterdam area, shows that the majority of the individuals in 2006 belonged to higher body-length classes than in 2007. The average body length of the shipworms at the end of the growing season in 2006 (n=334, M=15.5 cm, SD=5.5 cm) was significantly greater ($t(427)=4.1$, $p<0.001$) than the average body length of the shipworms at the end of the growing season in 2007 (n=95, M=12.8 cm, SD=6.3 cm). The longest individuals in 2006 and 2007 measured 36.9 cm and 28.8 cm, respectively (Table 3).

Between Oct. 3 and Dec. 10, 2006, the average body length of the individuals from the Calandkanaal increased by 10.5 cm, from 5 cm to 15.5 cm, a growth of 0.15 cm day^{-1}. If the individuals in the body-length classes 0–5 cm and 5–10 cm are considered to have settled after Oct. 3, 2006, then the growth would have been 0.18 cm day^{-1}.

Individuals found in the St-Laurenshaven, a harbour with strong fluctuations in salinity, all belonged to the 0–5 cm body-length class on Oct. 3 and Dec. 10, 2006. Growth of these individuals between these two dates amounted to only 0.02 cm day^{-1}. Body lengths of the individuals on Dec. 10, 2006 at the bottom on the locations 2, 4, 5, 7 en B in the Calandkanaal differed significantly (one-way ANOVA, $F(4,170)=5.3$, $p<0.001$). Those of location 5 (Weserhaven) were

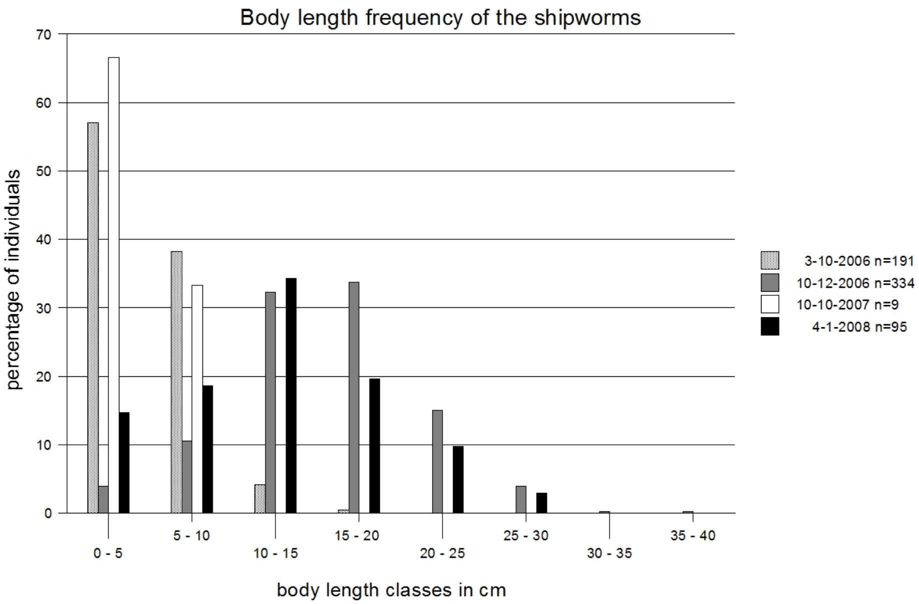

Figure 7 Body length frequency of the shipworms found in 2006 and 2007 in the fir panels as a percentage of the number of individuals. Data from all monitoring locations.

significantly longer than those of the locations 7 (Londonhaven) and B (Calandkanaal mouth). On the latter locations the panels felt dry during spring tide. Significant differences in body length in shipworms between the locations 2 (Scheurhaven), 4 (fourth Petroleumhaven) and the locations 7 (Londonhaven) and B (Calandkanaal mouth) were not seen.

In both 2006 and 2007 the body lengths of the individuals at the end of the growing season at different distance from the bottom over approximately the first metre differed significantly from one another (one-way ANOVA, $F(4, 232)=3.5$, $p<0.01$ and $F(4, 44)=2.8$, $p<0.05$) (Table 3). The largest shipworms were found closest to the bottom and around 1 m above the bottom. In both years a quadratic trend could be demonstrated between the distance from the bottom and the body lengths of the shipworms (one-way independent ANOVA, $F(1, 232)=8.3$, $p<0.01$ and $F(1, 44)=5.3$, $p<0.05$ for the years 2006 and 2007, respectively).

The individuals found in the oak wood panels at the bottom of the Scheurhaven (n=7, M=7.0 cm, SD=2.9 cm) on Dec. 10, 2006, were significantly shorter in body length ($t(43)=2.5$, $p<0.02$), than those found in the fir panels at the bottom of the Scheurhaven (n=40, M=11.6 cm, SD=4.8 cm) on the same date.

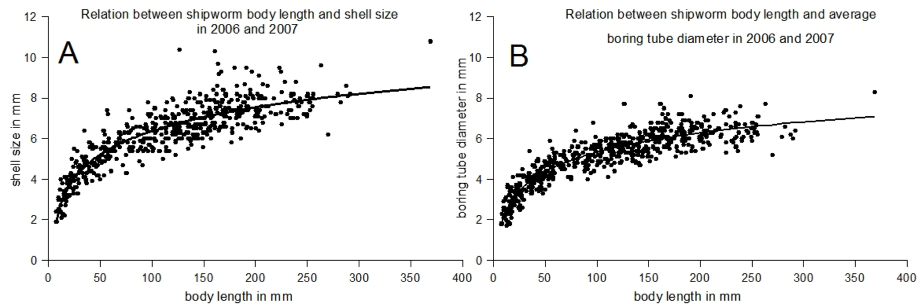

Figure 8 A. Relation between the shipworm body length and its shell size (Y = 1.69lnX – 1.38, R^2 = 0.78, p < 0.0001, N = 531), B. Relation between the shipworm body length and the average boring tube diameter in 2006 and 2007 (Y = 1.38lnX - 1.02, R^2 = 0.83, p < 0.001, N = 592). Data from all monitoring locations.

Shell length and body length of 531 individuals were measured in 2006 and 2007. A clear positive logarithmic correlation (R^2=0.78, p<0.0001) was found between the body length and size of the shell (Fig. 8A). The largest shell measured 10.8 mm. The boring tube changes from conical to cylindrical at a body length between 50 and 100 mm.

In 2006 and 2007 almost the same logarithmic relationship between the body length of the shipworms and the average tube diameter was found (Fig. 8B). In both cases there was a significant positive correlation (R^2=0.84, p<0.001 and R^2=0.76, p<0.001, respectively).

The wood loss by shipworms could be calculated by means of the average diameter of the boring tubes (Table 3). In 2006 most of the wood was lost within the panels on the bottom due to the higher shipworm infestation there than in the other panels. Within a period of 3 to 4 months 12.4 % of the fir wood was lost due to shipworm boring activity.

In 2007 the percentage wood loss was much lower, not only as a result of fewer shipworms within the panels but also because the individuals were smaller than in 2006 (Table 3). The amount of wood loss per individual shipworm in oak wood was less than half of that in fir (Table 3).

Discussion

The water temperatures measured at the mouth of the estuary indicate that during the monitoring period *T. navalis* could perform its boring activity almost year round, although it was reduced during winter. Taking 12˚C as the lower limit

Table 3 Wood loss due to the shipworm activity in 2006 and 2007 and their length in fir and oak panels and in fir beams (*) in the Scheurhaven. std = standard deviation, med = median, min = minimum, max = maximum.

date	distance in cm to bottom	type of wood	volume of wood in cm^3	number of shipworms	length of shipworms in cm					volume of wood loss in cm^3	% wood loss	volume of wood disappeared in cm^3 per shipworm
					mean	std	med	min	max			
3-10-2006	0 - 10	fir	2400	77	5.0	2.5	4.6	1.0	10.4	65.4	2.7	0.85
3-10-2006	25 - 35	fir	2400	46	4.7	3.0	4.1	0.8	14.6	37.0	1.5	0.81
3-10-2006	50 - 60	fir	2400	21	4.2	1.6	3.8	1.7	8.0	14.2	0.6	0.67
3-10-2006	75 - 85	fir	2400	14	4.5	2.3	4.1	1.1	9.8	10.8	0.5	0.77
3-10-2006	100 - 110	fir	2400	21	5.9	3.8	5.4	1.0	17.2	22.3	0.9	1.06
10-12-2006	0 - 10	fir	2400	74	15.8	4.4	15.9	4.3	27.9	297.6	12.4	4.02
10-12-2006	25 - 35	fir	2400	49	16.0	6.5	15.3	2.0	36.9	236.5	9.9	4.83
10-12-2006	50 - 60	fir	2400	41	13.3	5.1	13.2	1.8	25.0	146.0	6.1	3.56
10-12-2006	75 - 85	fir	2400	37	13.4	4.8	13.8	2.4	23.5	143.0	6.0	3.87
10-12-2006	100 - 110	fir	2400	32	16.5	5.2	17.1	3.5	24.7	145.9	6.1	4.56
10-10-2007	0 - 10	fir	4800	9	4.0	2.1	3.4	1.3	7.6	5.1	0.1	0.57
4-1-2008	0 - 10	fir	4800	40	11.6	4.8	11.8	1.8	21.3	123.1	2.6	3.08
4-1-2008	0 - 10	oak	4800	7	7.0	2.9	5.6	4.7	12.6	9.9	0.2	1.42
4-1-2008	0 - 20	fir*	4000	8	18.9	6.7	19	10.3	28.8	42.7	1.1	5.34
4-1-2008	20 - 40	fir*	4000	19	10.6	5.9	9.8	2.2	22.6	53.9	1.3	2.84
4-1-2008	40 - 60	fir*	4000	5	12.0	6.3	12.3	2.1	18.2	19.8	0.5	3.96
4-1-2008	60 - 80	fir*	4000	8	11.6	6.9	12.0	2.5	23.5	25.8	0.6	3.22
4-1-2008	80 - 100	fir*	4000	5	15.0	6.2	15.3	9.1	22.5	21.8	0.5	4.36

for reproduction, the spawning season could start in April/May and end at the beginning of November, but as no individuals were found before September, it is more likely that reproduction started in July/August based on settlement time.

The settlement of *T. navalis* in the port of Rotterdam area decreased with increasing distance from the bottom (sea floor) in both test panels and test beams; this was found also by Scheltema and Truitt (1956) in test panels in Maryland coastal waters, U.S.A., and by Tuente et al. (2002), who counted bore holes in oak piles and fir pier posts in the harbours of Bremerhaven in Germany. This pattern of settling could be an advantage in estuaries where salinities are usually higher and more stable near the bottom.

The shipworms in the port of Rotterdam grew rapidly in 2006 and 2007 and achieved maximum body lengths of 38.9 cm and 29.0 cm, respectively. The higher average body length in 2006 related to more wood lost is very likely the result of the higher water temperatures in that year compared to 2007. Kristensen (1979) observed a maximum body length growth of 0.7 mm day^{-1} of

first-year animals in Denmark. In the present study the average body length growth in 2006 of 1.5 mm day^{-1} exceeded this more than twofold, and considering a growth period of 130 days, the longest animal found should be the result of an average body length growth rate of 3 mm day^{-1}.
A significant relationship between the shell size and body length of the shipworm was found. The curve of the logarithmic formula supports the findings of Mann and Gallagar (1985) that the shape of the boring tube is a truncated cone progressing to a cylinder. The formula can be used to estimate the body length of the animals and thus the wood consumption by measuring the shell size, but it should only be used when densities are too high to measure individual tube lengths.
Significantly less shipworm larvae settled on the oak panels and showed less growth after metamorphoses than those that had settled on fir panels. This may be related to the greater hardness of oak wood, which means that the animals need to spent more energy boring into oak than into fir. Within specialized epithelial cells of several members of the Teredinidae, associations of symbiotic cellulolytic nitrogen-fixing bacteria were found within the gills (Distel et al., 1991, 2002*,* Sipe et al., 2000). Popham and Dickson (1973) demonstrated bacterial associations in the gills of the shipworm *T. navalis,* indicating that this species may be able to feed solely on wood. Mann and Gallager (1985) found no significant growth enhancement in the presence of a phytoplankton supplement (in addition to wood). However it is not unlikely that individuals that bore into hardwood need to acquire extra nourishment by filtration for at least their basal metabolism. This is also the case in highly infested wood when there is no more space to bore into left.
In the port of Rotterdam *T. navalis* seems to have a vital population in the Caland- and Beerkanaal from which larvae are transported by the tidal currents via the Hartelkanaal and Nieuwe Waterweg where, as demonstrated for a few locations, they can settle and survive for a short period of time. Taking into account the high river discharges that occur with the low salinities they bring about, it is not possible that a viable *T. navalis* population could be built up other than in the polyhaline environment of the Caland- and Beerkanaal. The presence of *T. navalis* in panels in the St-Laurenshaven showed the ability of the larvae to travel upstream of at least 20 km.

Conclusions

The area of distribution in the port of Rotterdam of the shipworm *T. navalis* encompasses the polyhaline harbours Beer- and Calandkanaal. Under conditions of low river discharge the area of distribution can temporarily be

extended to some 20 km upstream via the Nieuwe Waterweg. Based on the water temperature in the period 2004-2008, the potential breeding season lies between April and November. Based on the settlement on fir panels, a breeding season between July and November is more likely for the port of Rotterdam area.
Considering the water temperature in the period 2004-2008 the shipworm could have performed its boring activity 94% of the time. This is almost year round. The historical river discharge changes make it plausible that the shipworm could settle for a short period of time in the eastern part of the port of Rotterdam area. The settlement of the shipworm in the port of Rotterdam area showed a clear negative correlation to its distance to the bottom.
Shipworms in the port of Rotterdam area grew with an average body-length growth rate of 1.5 mm day^{-1} in 2006 and caused a loss of 12.4% of the fir wood of panels at the bottom of the Scheurhaven in a period of approximately 4 months. Significantly less shipworm larvae managed to settle in oak wood than in fir wood. The growth of shipworm individuals in oak wood was significantly lower than in fir wood.
Although there is a strong statistical relation between the shell size and the body length of the shipworm, the shell size should only be used to calculate the length of an individual if not exceeding 5 to 6 mm. At high densities measurement of the shell sizes could be appropriate to calculate wood consumption in the first season after settlement. There is a significant relation between the length of the shipworm and its average boring tube diameter, but as the individuals grow longer this relation becomes weaker.
Lower river discharges leading to salinisation of the eastern part of the port of Rotterdam area create conditions favourable for the shipworm to settle and grow, with consequences for the condition of the piles upon which the quays are built.

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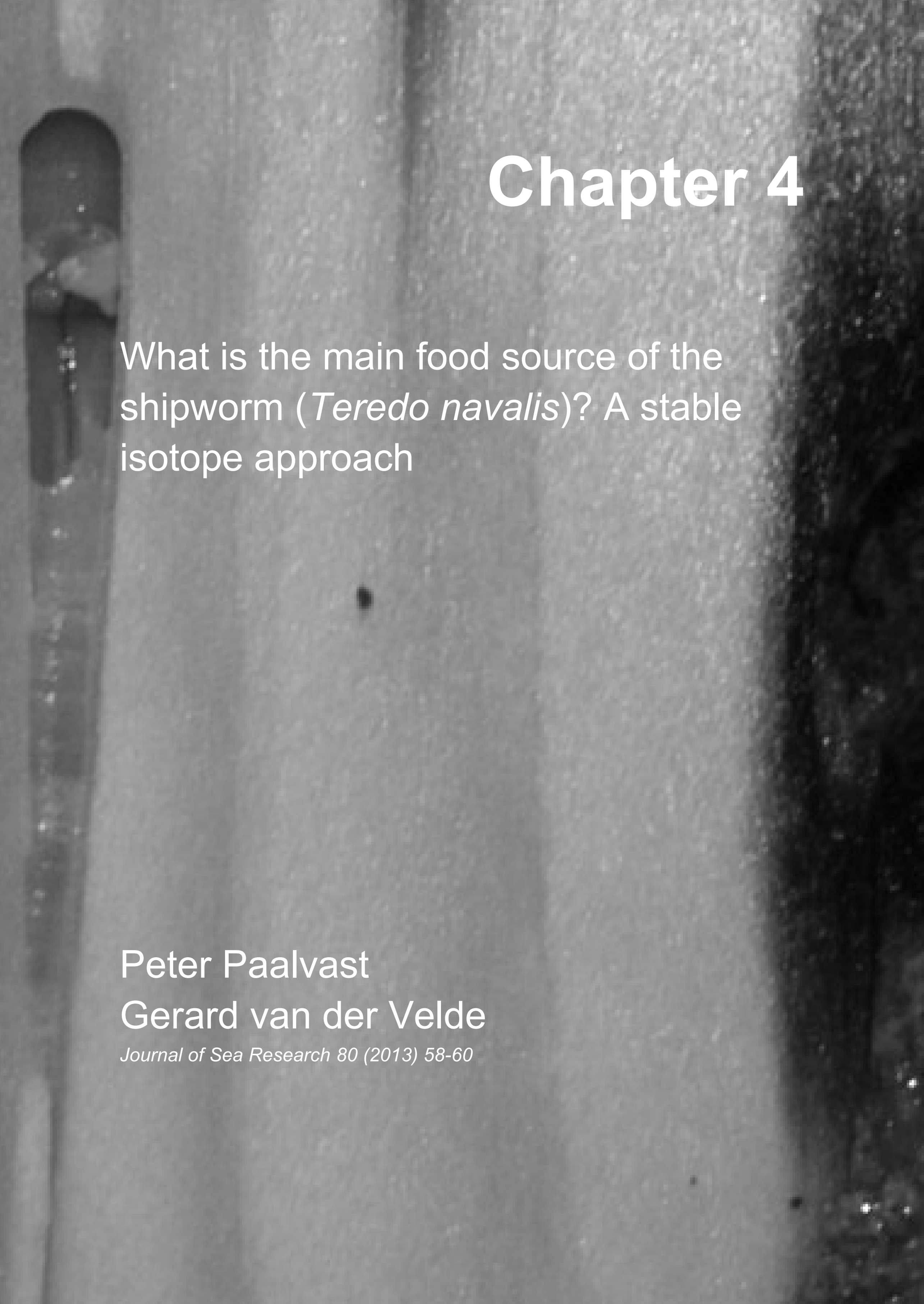

Chapter 4

What is the main food source of the shipworm (*Teredo navalis*)? A stable isotope approach

Peter Paalvast
Gerard van der Velde

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Abstract

Stable isotope analysis of soft bodies of the shipworm *Teredo navalis* demonstrated that this species is mainly feeding on seston by filter feeding in contrast to wood consumption. *Teredo navalis* showed similar stable isotope values ($\delta^{13}C$, $\delta^{15}N$) as *Mytilus edulis* and *Crassostrea gigas*, which species were attached to the wood instead of boring into.

Introduction

Boring behaviour protects bivalves against predation while they filter feed consuming seston. Within boring bivalves belonging to the Pholadacea two families are usually distinguished viz. Pholadidae (Angel Wings) which bore into hardened peat, wood, soft chalkstone, corals (and even ABS pipes e.g. Jenner et al., 2003) and Teredinidae (Shipworms) which are specialized to bore into wood (Turner, 1966). It is an ongoing debate if some species of the Teredinidae are able to feed on wood exclusively, or on symbiotic bacteria feeding on wood or also feed on seston (suspended organic matter: plankton and detritus) as additional or as main food source (e.g. Nair and Saraswathy, 1971, Pechenik et al., 1979 and literature therein).

Within specialized epithelial cells of several members of the Teredinidae, associations of symbiotic cellulolytic nitrogen fixing bacteria were found within the gills (Distel et al., 1991, Distel et al., 2002, Sipe et al., 2000, Betcher et al., 2012). Wood contains a very low level of nitrogen and has so a very high C/N ratio (Distel, 2003) and therefore the atmospheric nitrogen usable for some shipworm species fixed by endosymbionts (Lechene et al., 2007) may be the main source.

One of the most common teredinid species is *Teredo navalis*. Popham and Dickson (1973) demonstrated bacterial associations in the gills of *T. navalis* indicating that this species may be able to feed solely on wood. Mann and Gallager (1985) found no significant growth enhancement in the presence of a phytoplankton supplement (in addition to wood), which could suggest wood as the primary food resource. Paalvast and Van der Velde (2011) suggest that individuals that bore into hardwood need to acquire extra nourishment by filtration for at least their basal metabolism, and that this also accounts in highly infested wood when there is no more wood left to bore into.

To find out what *T. navalis* is mainly consuming can nowadays be tested by stable isotope analysis. Carbon isotope ratios ($\delta^{13}C$) in animal tissues closely resemble the food consumed over longer period of time, meaning you are (almost) what you eat. The enrichment in $\delta^{13}C$ in the consumer compared with its diet lies within 0 to 1‰ (DeNiro and Epstein, 1978, Rau et al., 1983, Fry et al., 1984, Gu et al., 1996, Vander Zanden et al., 1997, Vander Zanden et al., 1999). The nitrogen ratio ($\delta^{15}N$) increases by 3.4 ± 1.1‰ with each trophic level through the food web (DeNiro and Epstein, 1978, Minagawa and Wada, 1984, Wada et al., 1987). $\delta^{13}C$ values indicate the carbon sources, while $\delta^{15}N$ values indicate trophic position.

We hypothized that, when *T. navalis* feeds mainly on wood as a carbon source the $\delta^{13}C$ values of the shipworm would resemble the $\delta^{13}C$ values of the wood in which they bore into. When *T. navalis* feeds on seston by filter feeding, than the $\delta^{13}C$ values of the shipworm resemble the $\delta^{13}C$ values of other bivalve filter feeders at the same location. We further hypothesized in the case of filter feeding on seston the $\delta^{15}N$ values of the shipworm are expected to be at least 3.4 ± 1.1‰ higher than the $\delta^{15}N$ of wood and should be similar to the $\delta^{15}N$ values of other bivalve filter feeders at the same location.

Material and methods

To test the above hypotheses the carbon and nitrogen stable isotope composition of the body tissue of the bivalves *T. navalis* (shipworm), *Mytilus edulis* (Blue mussel) and *Crassostrea gigas* (Pacific oyster) and the fir wood (*Picea abies*) where they lived in or on wood, was analysed.
The shipworms, blue mussels and Pacific oysters were all collected from the last metre near the sea floor of 8 metre long fir beam that was attached to a mooring pole from 3 metres above the mean low water level (MLWL) till the bottom of the sea floor 5 m below MLWL in the polyhaline Scheurhaven of the port of Rotterdam, the Netherlands (51º 57' 43.33" N, 4º 8' 16.41" E). The fir beam was attached to the mooring pole in April 2009 and removed in April 2012. The last metre of the pole was cut off and transported to the laboratory of the Radboud University Nijmegen. Mussels and oysters that grew on the beam were removed, shipworms were retrieved by cutting and splitting the beam with an axe and samples of the wood were taken for stable isotope analysis.
In the laboratory, bivalves were rinsed first in tap water and then in distilled water. The soft bodies of 6-8 individuals were pooled for each sample and oven dried at 60 °C for 3-5 days. Shells of molluscs and pallets in the case of the shipworm were removed and the remaining body tissue dried for 48 h at 60°C, after which specimens were ground to a fine powder using a pestle and mortar and liquid nitrogen. Measurements were carried out for each individual using their powder stored in small new glass bottles with a plastic cap until weighing. Carbon and nitrogen stable isotopic compositions were measured with a Carlo Erba NA 1500 elemental analyzer coupled online via a Finnigan Conflo III interface with a ThermoFinnigan DeltaPlus mass spectrometer. Carbon and nitrogen isotope ratios are expressed in the standard delta notation ($\delta^{13}C$, $\delta^{15}N$) relative to Vienna PDB and atmospheric nitrogen. Average reproducibility based on replicate measurements of internal standards Sucrose (IAEA-CH-6) for $\delta^{13}C$ and Ammonium sulphate (IAEA-N-2) for $\delta^{15}N$ was ca. 0.15‰. Acetanilide was used as the laboratory reference.

Statistical analysis was carried out with SPSS 15.0 for Windows. Anova together with the Levene's test for equality of variance was conducted to compare the means of $\delta^{13}C$ and $\delta^{15}N$ of the species involved.

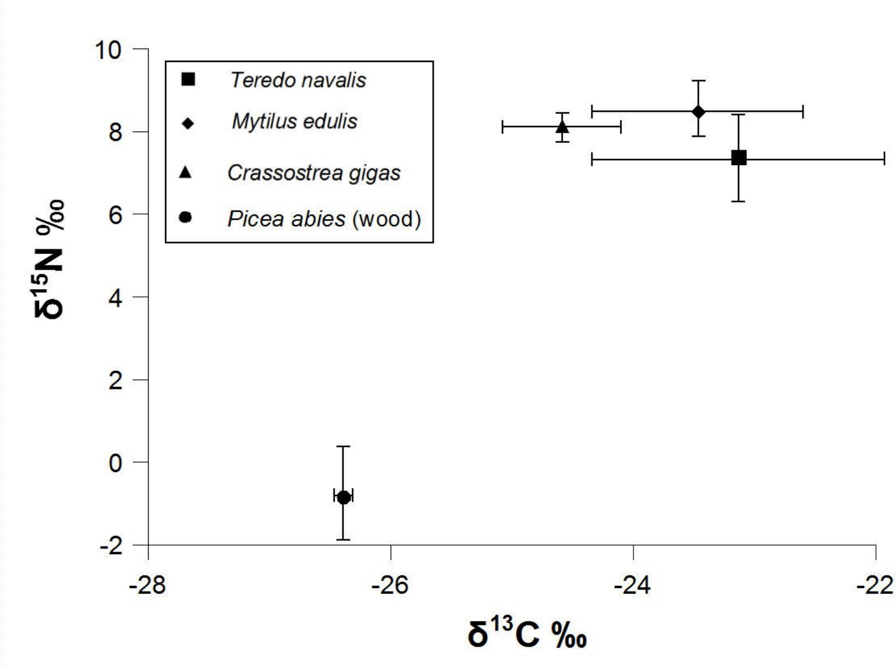

Figure 1 Stable isotope values for the shipworm (*Teredo navalis*), Blue mussel (*Mytilus edulis*), Pacific oyster (*Crassostrea gigas*) and wood (*Picea abies*).

Results

As fir wood contains very little nitrogen this led to overflow of 5 of the 9 samples during the stable isotope analyses for this element, but this was not the case for carbon. All other samples did not show any overflow.

There was a significant difference in the means of $\delta^{13}C$ values between the species (one-way ANOVA, $F(3,52)= 31.1$, $p< 0.001$) (Fig. 1). Wood (N = 9, M ($\delta^{13}C$) = -26.41 ‰, SE = 0.023) compared with the bivalves had a significant (Tamhane at the 0.05 level) lower $\delta^{13}C$ value ranging from -1.8‰ for the Pacific oyster (N = 8, M ($\delta^{13}C$) = -24.58 ‰, SE = 0.213), -3.0‰ for the Blue mussel (N = 23, M ($\delta^{13}C$) = -23.46 ‰, SE = 0.181) to -3.3‰ for the shipworm (N = 16, M ($\delta^{13}C$) = -23.13 ‰, SE = 0.302). Furthermore the Pacific oyster's $\delta^{13}C$ was significantly lower (Tamhane at the 0.05 level) than those of shipworm and Blue mussel.

There was also a significant difference in the means of $\delta^{15}N$ values between the species (one-way ANOVA, $F(3,47) = 170.6$, $p < 0.001$) (Fig. 1). Wood (N = 4, M ($\delta^{15}N$) = -0.86 ‰, SE = 0.538) compared with the bivalves had a significant (Tamhane at the 0.05 level) lower $\delta^{15}N$ value ranging from -8.2‰ for the shipworm(N = 16, M ($\delta^{15}N$) = 7.38 ‰, SE = 0.251), -9.0‰ for the Pacific oyster(N = 8, M ($\delta^{15}N$) = 8.14, SE = 0.120) to -9.3‰ for the Blue mussel (N = 23, M ($\delta^{15}N$) = 8.48 ‰, SE = 0.130). Between the bivalves there was only a significant difference between the mean $\delta^{15}N$ values of the shipworm and the Blue mussel.

Discussion

Several species of shipworms including *Teredo navalis* seem to be able to grow in the absence of food (apart from wood) as demonstrated under laboratory conditions (Gallager et al., 1981, Man and Gallager, 1985). The presence of phytoplankton supplement enhanced growth in the shipworm, *Bankia gouldi*, but was progressively less significant in the shipworms *T. navalis* and *Lyrodus pedicellatus* (Man and Gallager, 1985). Becker (1959, in Nair and Sarawathy) managed to rear *L. pedicellatus* through four generations in artificial sea water without any additional food. He was unsuccessful with *T. navalis* that failed to breed probably on account of inadequate nutrition, owing to the absence of protein rich plankton. Mann and Gallager (1985) observed well developed gonads with sperm and ova present for *Bankia gouldi* in the absence of planktonic food but did not mention this for *T. navalis* as gonad development was not part of their study. Turner (1966) suggested that the adults of some species require planktonic food during the breeding period, while others may be capable of surviving on plankton only as do many other bivalves.

The $\delta^{13}C$ values of the shipworm *T. navalis* were on average 3.3‰ higher than that of the wood it lived in. This is far above the range of 0 to 1‰ if wood would have been the main source of carbon. The shipworm's $\delta^{13}C$ values closely resembled the $\delta^{13}C$ values of the Blue mussel and were higher than the $\delta^{13}C$ values of the Pacific oyster. This means that not the wood it bores into but food obtained by filter feeding via the siphons was the main source of carbon, despite the presence of possible symbiotic cellulolytic nitrogen fixing bacteria in the gills of this species of shipworm. It further indicates that under natural conditions drilling in wood by the shipworm, *T. navalis*, is more important for shelter than nutrition.

The positive difference between the $\delta^{15}N$ of the bivalves compared with the $\delta^{15}N$ of wood was more than twice the 3.4 ± 1.1‰ value for each consecutive trophic level through the food web (DeNiro and Epstein, 1978, Minagawa and Wada,

1984, Wada et al., 1987), further the $\delta^{15}N$ of the shipworm was very close to the $\delta^{15}N$ of the Blue mussel and Pacific oyster. This excludes wood as the main source for nitrogen, and that food must have been acquired by filter feeding of seston. It would be very illogical that food present in the inhaled water would not be utilized as a carbon and nitrogen source.
This means that under natural conditions symbiosis between shipworm, *T. navalis*, and endosymbionts is not a case of mutualism but rather of commensalism from the latter.

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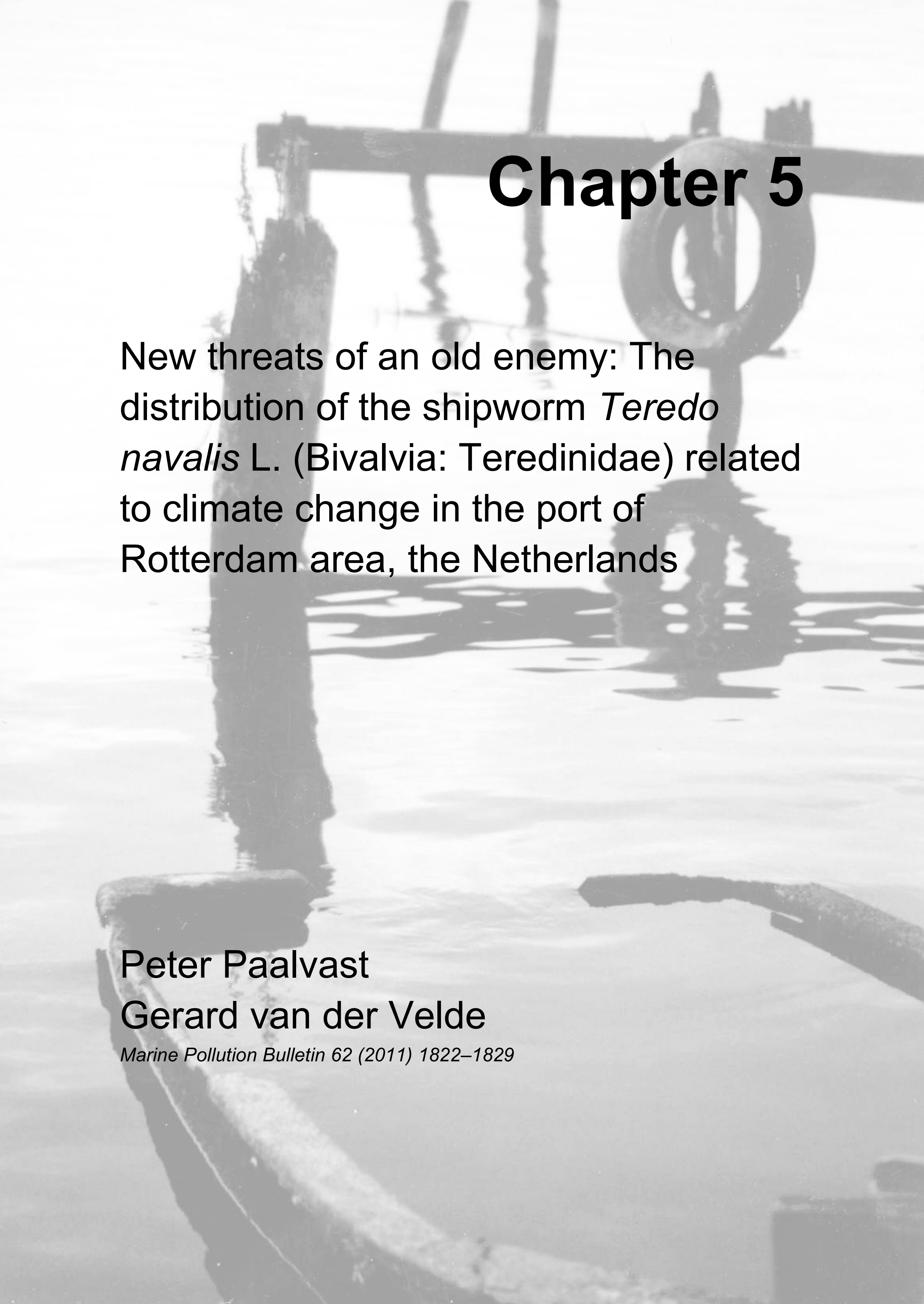

Chapter 5

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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Gerard van der Velde

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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).

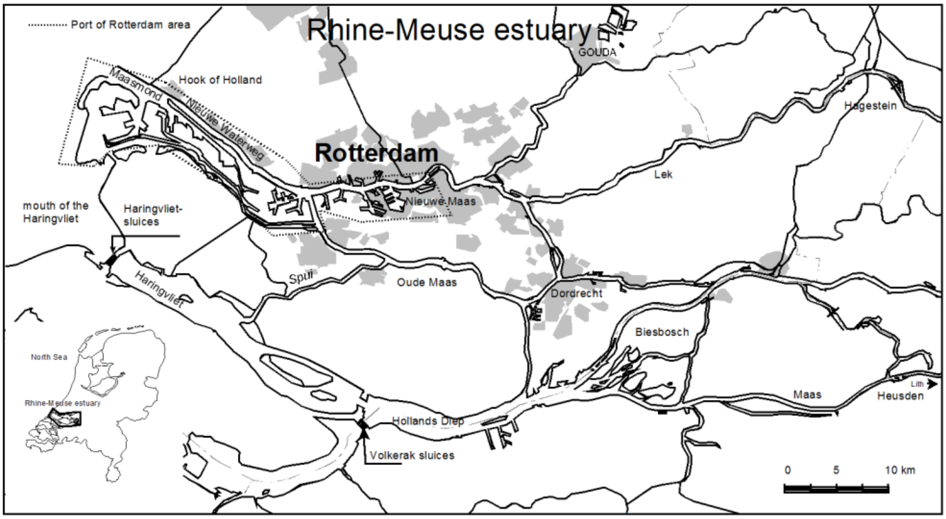

Figure 1 The port of Rotterdam in the Rhine-Meuse estuary.

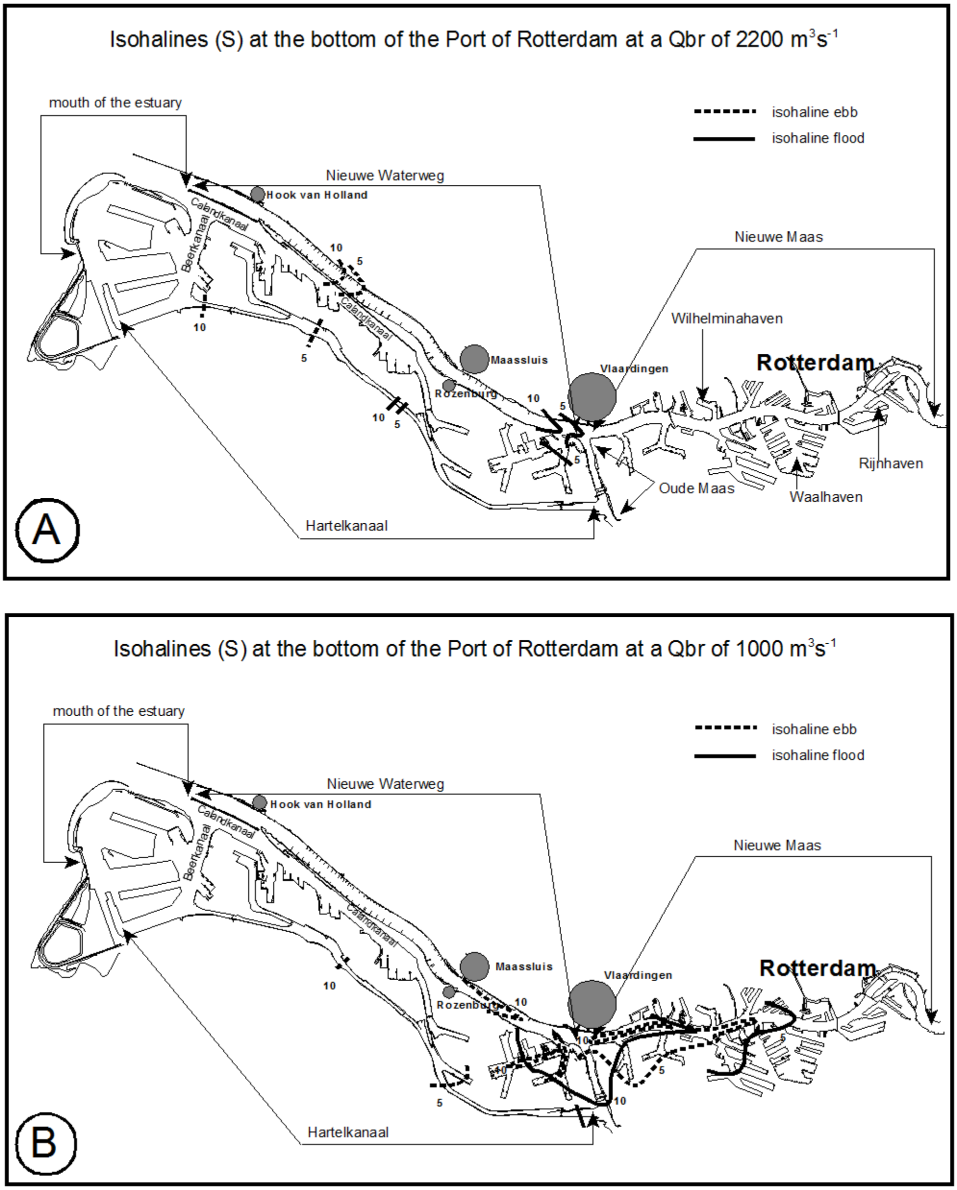

Figure 2 (A) The 5 and 10 isohalines during ebb and flood periods in the port of Rotterdam area under an average discharge of the Rhine at the Dutch-German border (Qbr) of 2200 $m^3 s^{-1}$. (B). The 5 and 10 isohalines during ebb and flood periods in the port of Rotterdam area under a discharge of the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

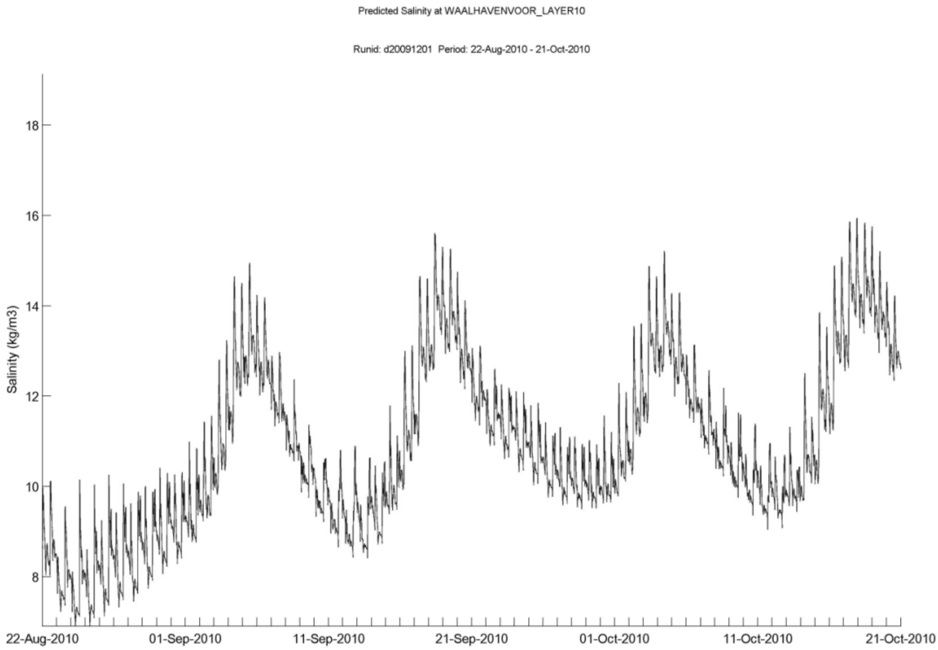

Figure 3. Example of the output of the SIMONA hydraulics knowledge system at a Qbr of 700 $m^3 s^{-1}$ for the salinity at the sea floor of the Waalhaven in the eastern part of the port of Rotterdam area.

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.

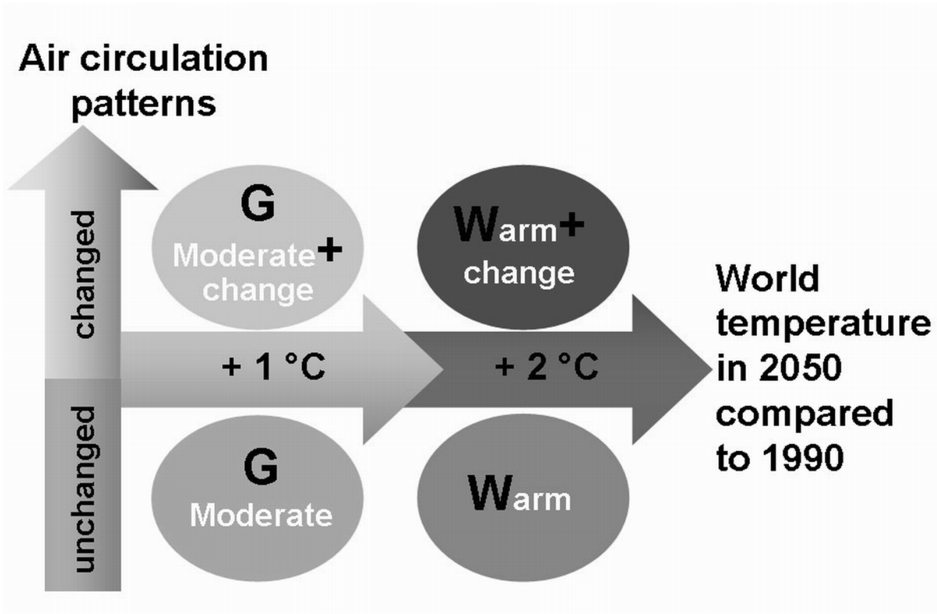

Figure 4. Schematic overview of the four KNMI’06 scenarios (after Van den Hurk, et al., 2006).

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.

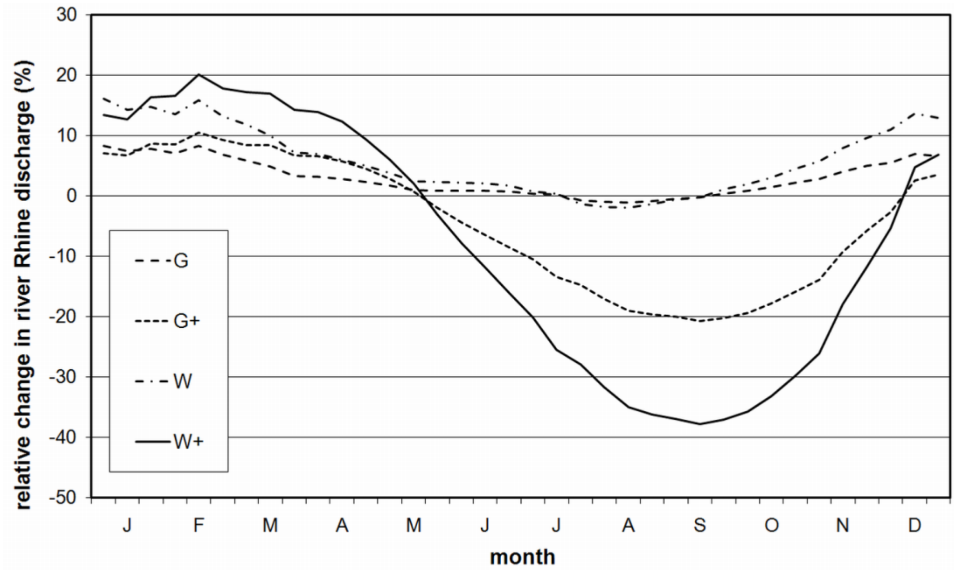

Figure 5. Simulated relative change in the discharge of the Rhine river as a consequence of the KNMI'06 scenarios (after Van Deursen, 2006).

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.

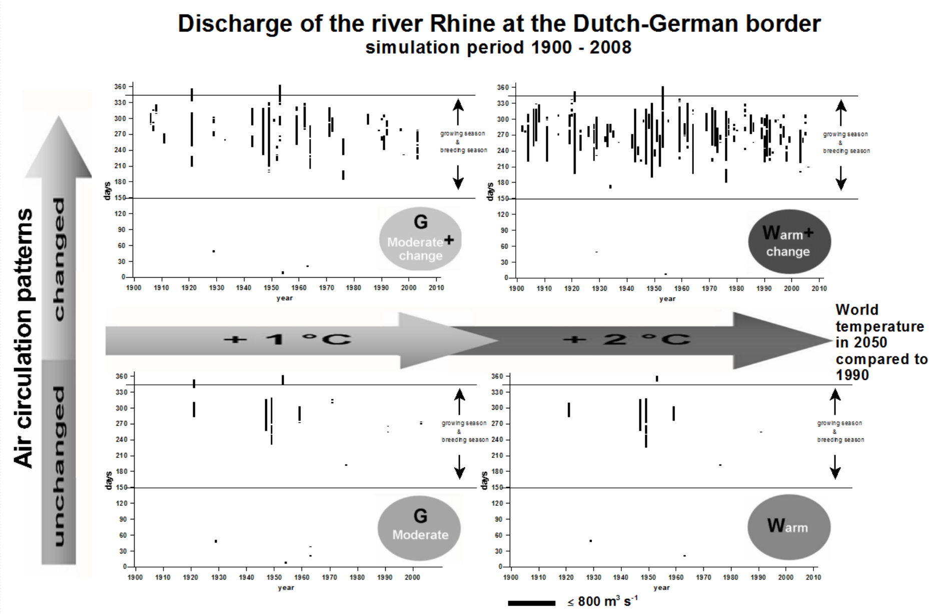

Figure 7. Simulated periods of discharges of the Rhine river at the Dutch-German border of ≤ 800 $m^3\ s^{-1}$ during the period 1901- 2008 and their occurrence in the breeding and growing season of the shipworm as a consequence of the KNMI'06 scenarios.

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.

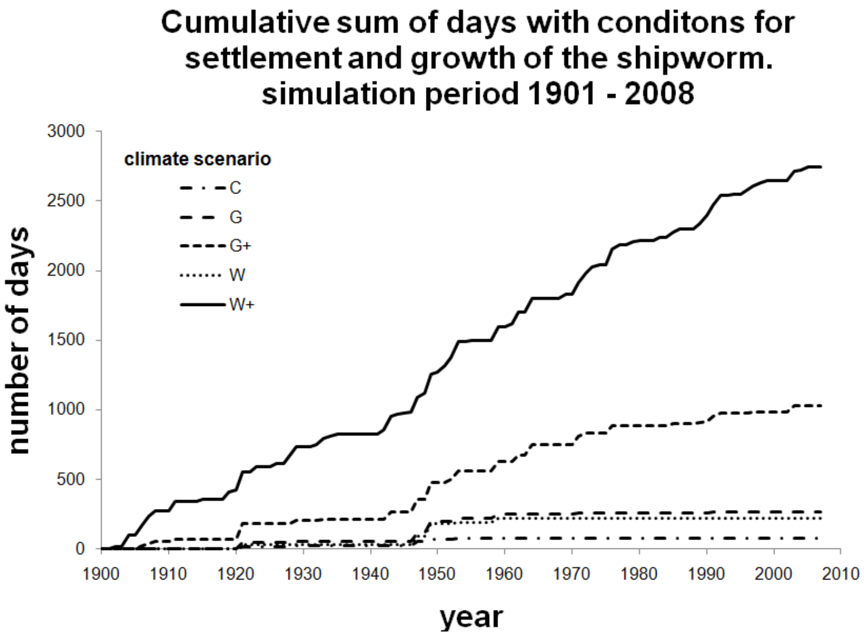

Figure 8. Cumulative sum of events with potential shipworm damage in the eastern part of the Port of Rotterdam under the prevailing climate conditions (*C*) and the KNMI'06 scenarios as simulated for the period 1901 – 2008.

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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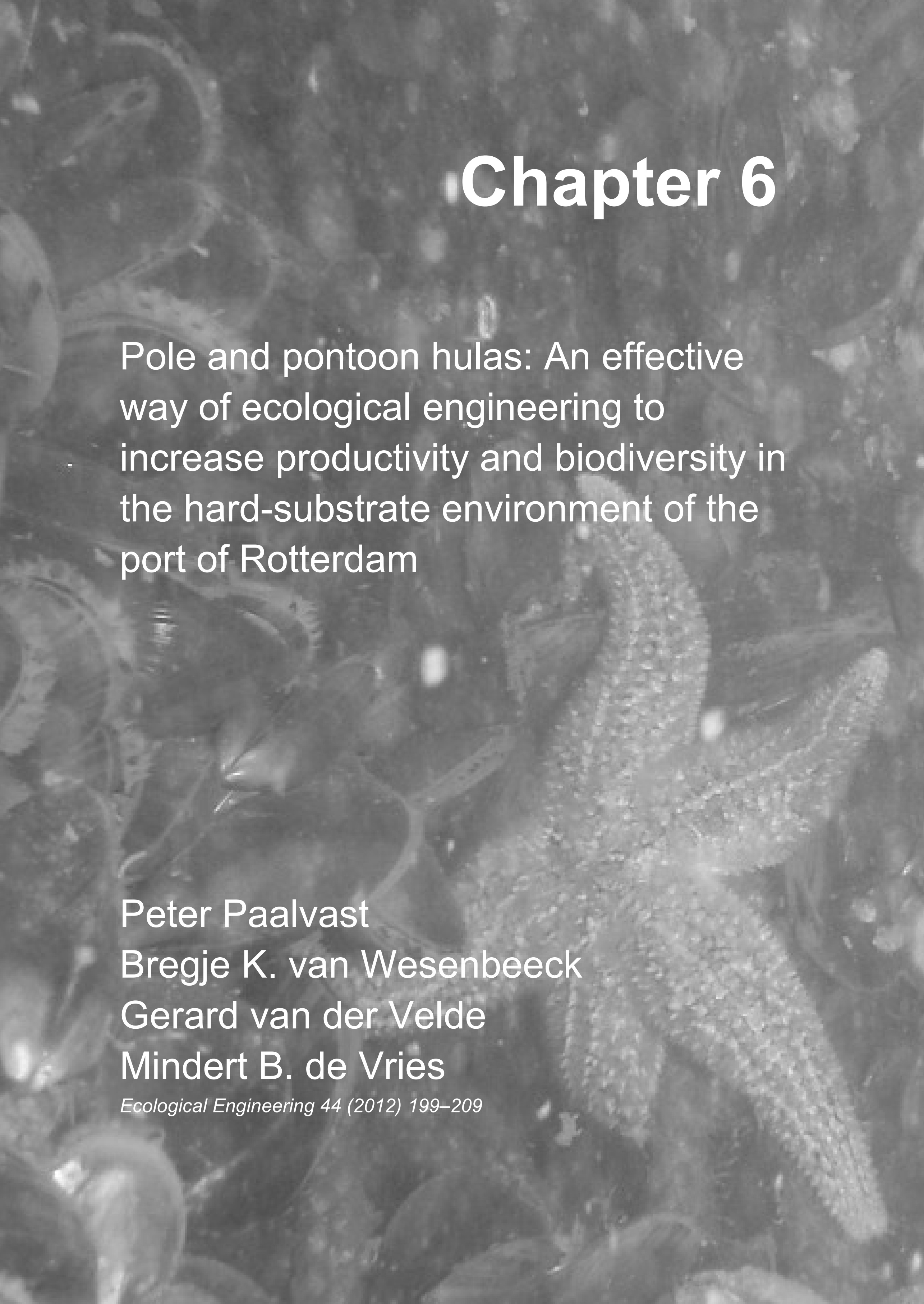

Chapter 6

Pole and pontoon hulas: An effective way of ecological engineering to increase productivity and biodiversity in the hard-substrate environment of the port of Rotterdam

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Abstract

Underwater environments in ports are designed for harbour activities solely. However, by simple and cost-effective measures, suitable habitat for underwater flora and fauna can be created. This is expected to have positive effects on higher trophic levels, such as fish, and improve water quality, by enlarging filter feeder biomass. In this study we developed 'pole hulas' and 'pontoon hulas', consisting of hanging ropes of different materials. The pole hulas are made up of many 6 mm thick and 55 cm long strings just above and below the mean low water level (MLWL) around poles. The pontoon hulas resemble raft like structures with 12 mm thick and 150 cm long ropes within the open space of mooring pontoons. The first experimentation with these structures was executed in the polyhaline harbours of the port of Rotterdam. The pole hulas were rapidly colonized by a variety of organisms. Above MLWL a seaweed community dominated on the strings. Below MLWL *Mytilus edulis* (the Blue mussel) was found to be the dominating species after a few months. In the dense layer of *M. edulis* on both pole hulas and pontoon hulas many mobile soft-bottom amphipods and young ragworms occurred, which means that colonisation on these structures compensate for biodiversity loss of bottom fauna due to dredging and disturbance by propellers of ships. Settlement of the exotic *Crassostrea gigas* (Pacific or Japanese oyster) did not occur on the strings of the pole hulas, the ropes of the pontoon hulas and not on the poles with hulas.

Wet biomass (including shells) on pole hulas was positively correlated with depth and on average 4.4-11.4 higher compared to biomass on reference poles. Colonization of the pontoon hula ropes was similar to colonization of the pole hulas below MLWL. Biomass production per rope was density dependent and optimal density of ropes was estimated at 4 to 8 ropes m^{-2}. Biomass (mainly *M. edulis*) on the ropes of pontoon hulas decreased to a half from the edge to the heart of the hula demonstrating the limitation of food by competition.

It was concluded that ecological engineering in the port of Rotterdam with simple structures such as pole and pontoon hulas strongly enhances sessile biological production and biodiversity. This is likely to result in a positive impact on local water quality, and, if applied at larger scales, may have positive influences on the remains of Rhine-Meuse estuary.

Introduction

Various large ports all over the world have come to development over centuries and are situated as far land inwards the estuary as ancient ships could sail. Systematic dredging for greater depth of the waterways and canalization started in the 19th century. Together with agriculture, urbanization, industrialization and port development, this exerted a strong influence on the estuarine ecosystem. In estuaries such as the Elbe (Reky, 1992) and the Seine (Lesueur and Lesourd, 1999) most marshes were used for land reclamation and sand and mudflats disappeared due to hydrological changes. Within the Humber estuary some 50% of the original intertidal zone area was sacrificed for human activity (Jones, 1988).

The port of Rotterdam is situated in the remains of the Rhine-Meuse estuary. Before the Delta Works (Smits et al., 2006) that closed most of the river mouths with dams and barriers (1958–1986), the intertidal zone of the estuary consisted mostly out of beaches, salt and brackish marshes, sand and mud flats, tidal creeks, immense fresh and brackish rush and reed beds and intertidal forests. In the northern part of the Rhine-Meuse estuary many of these soft substrate ecotopes disappeared gradually with the development of the port of Rotterdam between 1870 and 1970 (Paalvast, 2002). At present along the salinity gradient no more than 3 ha of brackish marshes, rush and reed beds are left, and due to canalization the tidal creeks and the natural sand and mud banks have disappeared completely (Paalvast, 2002). Between 1960 and 1970 the pollution of the port of Rotterdam was severely degrading the ecosystem to a low number of pollution tolerant species (Wolff, 1978). However, since the 1970's the water and sediment quality has been improved. This was due to the lowering of pollutants in the river Rhine in particular as a result of the Rhine Action Plan after the Sandoz accident in 1986 (Admiraal et al., 1993, Huisman et al., 1998, Middelkoop and Van Haselen, 1999, Bij de Vaate et al., 2006). But also the ban of TBT, dredging and removal of the heavily polluted sediment, prevention of oil spills and the change from a bulk harbour to a container harbour contributed to a better water and sediment quality (Anonymous, 1999, Anonymous, 2006).The development of the port of Rotterdam transformed a formerly soft sediment habitat into a habitat that is mainly dominated by hard structures such as retaining walls, rip rap, piers, quays, pontoons, and mooring poles of concrete, hardwood and steel. These structures were quickly colonised by hard substrate communities and it is known that although distinct such 'artificial reefs' on the long-term may resemble natural reefs (Burt et al., 2011).

In 1964 the Japanese or Pacific oyster *Crassostrea gigas* was deliberately introduced by oyster farmers in the Eastern Scheldt in the Netherlands

(Duursma et al., 1982) and has since then spread over the brackish and salty waters of the Netherlands and abroad. In the Rotterdam port area *C. gigas* was observed for the first time in 1994 and has expanded since that time greatly over the past 15 years (Paalvast, 1995, 1998, 2008) mainly at the expense of the native Blue mussel *Mytilus edulis*. Nowadays *C. gigas* occupies almost all hard substratum including the pontoons and pier and mooring poles, while *M. edulis* is mainly confined to a narrow zone around the mean low water level (MLWL).

Ecological engineering was defined by Odum and Odum (2003) as the practice of joining the economy of society to the environment symbiotically fitting technological with ecological self design. Ecological engineering is common practice along rivers (Leuven et al., 2006) and was applied in coastal protection of the Netherlands on an experimental scale (Borsje et al., 2011). Such ecological engineering is rarely applied in port development (De Wit et al., 2007).

Considering the position of these large harbour water bodies within the Rhine-Meuse estuary implicating an enormous supply of nutrients and detritus by the river, ecological engineering by the enrichment of the aquatic environment with simple cost-effective under water structures that means surface enlargement and increased structure diversity for settlement, could enhance bioproductivity in particular of filter feeders as well as biodiversity. Fibrous structures are well known (since the 13th century) for their rapid colonisation by a variety of aquatic organisms particularly mussels (Veverica, 1982, Bompais et al., 1991, Pulfrich, 1996). Fibrous structures were chosen to test how far bioproductivity as well as biodiversity could be improved. “Pole hulas” (paalhula’s in Dutch), hula skirt liked rope structures were attached to wooden and steel poles, and “pontoon hulas” (pontonhula’s in Dutch) raft liked structures with ropes were placed in the enclosed space of the floaters of mooring pontoons.

The main goal of the present study is to get an answer on the question if pole and pontoon hulas can serve as tools for ecological engineering in a man-made estuarine environment, the port of Rotterdam. Therefore the following research questions were formulated: (a) How proceeds the colonisation and the succession of the fouling community on pole and pontoon hulas, (b) Can colonisation on pole and pontoon hulas compensate for biodiversity loss of the bottom fauna due to dredging and disturbance by propellers of ships, and reduce the settlement of the exotic Pacific oyster? (c) How does biomass production of the fouling community on pole and pontoon hulas develops in time? (d) Is biomass production on poles with hula’s higher than on those without? (e) Is biomass production on the pole hulas related to their position relative to the MLWL?, (f) Does competition exist between the fouling organisms on different ropes of the pontoon hulas, and does rope density on pontoon hulas influence the biomass production?

Material and methods

Study area

The Beer- and Calandkanaal are two large man-made polyhaline tidal water bodies (>2200 ha) in the westward part of the port of Rotterdam (Fig. 1).

Location

The colonisation experiment with pole and pontoon hulas was carried out in two small harbours, the Scheurhaven and the Pistoolhaven (Fig. 1). The Scheurhaven is a small working harbour with a length of over 300 m and a width of 100 m at the MLWL (mean low water level). The depth of the port is variable and ranges between 3.5 and 9.5 m below MLWL. Due to its location with access to the southeast, the Scheurhaven is a lee port. Waves, even in big storms, and tidal currents are negligible. However, there is 24-h activity of in and outgoing tugs and their propellers produce strong water currents, resulting in sediment resuspension. The average tidal range is 1.94 m. At springtide the tidal cycle exhibits approximately a 4 h period of flood, a 4 h period of ebb and a 4.5 h low water period. The water is often clear with a Secchi depth up to 3 m. The water is always polyhaline and depending on the river discharge there is a more or less clear vertical gradient in salinity with high salinity near the sea floor and a lower salinity at the water surface (Paalvast and Van der Velde, 2011).

The Pistoolhaven is one of the home ports of pilot tenders and has a length of 165 m and a width of 110 m at MLWL. At low tide the harbour is about 6 m deep. The abiotic conditions are similar to those of the Scheurhaven, but with wider salinity fluctuations and due to its entrance to the west waves are slightly higher. There is no significant resuspension of sediment by the tenders.

Pole and pontoon hulas

A pole hula is a synthetic free-hanging rope work that can be attached around wooden and steel poles. It consists of a 10 cm high hollow band made of a heavy quality plastic canvas on the top. In the seam of the band strings of 55 cm long with a diameter of 6 mm are sewn (Fig. 2). Per metre band there are 167

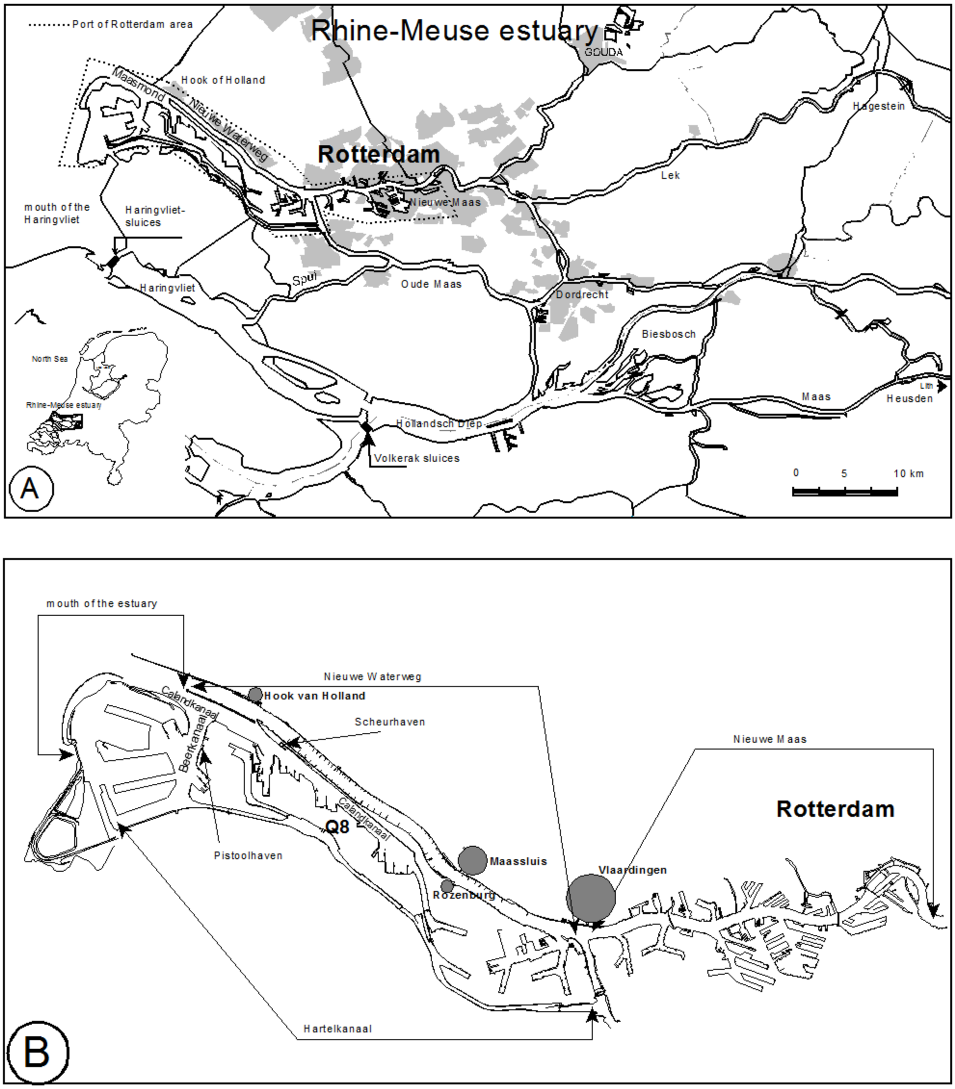

Figure 1 (A) The port of Rotterdam in the Rhine-Meuse Estuary. (B) The location of the Scheurhaven and the Pistoolhaven in the port of Rotterdam. Relevant temperature gauges are located at Hoek van Holland in the Nieuwe Waterweg and Q8 in the Hartelkanaal.

strings with a total length of 92 m. Through the hollow band runs a 25 mm wide nylon strap which at one end has a stainless steel rattle that is fixed on the band. With the rattle the pole hula can be attached tightly around a pole. For monitoring purposes, six counter buckles are stitched to the hollow band at equal distances. To each buckle four strings with a label are fastened. Pole hulas with polyamide strings that float are placed at intertidal levels and pole hulas with nylon strings that sink are attached subtidally (Fig. 2).
Pole hulas were mounted on five wooden poles in the Scheurhaven on the 9th of March 2009. Each pole contained four hulas, one with polyamide strings at 50 cm above MLWL and three with nylon strings with an overlap of approximately 10 cm at 0 cm, 50 cm and 100 cm below MLWL. On two steel poles in the Scheurhaven, three pole hulas were mounted below MLWL, because a hula above MLWL would be scraped off the pole by the pontoon that moves up and down with the tide. Fouling organisms were removed from all poles, including five wooden and two steel reference poles, with a high pressure sprayer (200 bars) between 1 m above and 2 m below MLWL.
A pontoon hula consists of a floating frame which is made of PVC sewer pipe with a diameter of 125 mm. Within this frame a nylon net with a mesh size of 12.5 cm x 12.5 cm is mounted. At the knots of the net nylon ropes with a diameter of 12 mm are attached. By the cross of the frame numbered counter buckles are attached to the knots of the net. Each counter buckle contains a numbered rope for monitoring purposes. The length of the rope and the string density varies per pontoon hula. There are two types (Fig. 3). Type I consists of ropes with a length of around 150 cm, and type II contains varying rope lengths, ranging from 30 cm in the middle to 150 cm at the outside with 20 cm differences between adjacent ropes (bell type). Hulas were placed in both harbour basins on the 16th and 17th of March 2009. In the Scheurhaven a type I and type II pontoon hula measuring 160 cm x 200 cm with both 208 ropes, and in the Pistoolhaven three type I pontoon hulas D16, D32 and D64 (with respectively 16, 32 and 64 ropes m^{-2}) measuring 85 cm x 230 cm were placed in the enclosed space of the floaters of mooring pontoons (Table 1).

Salinity, oxygen and temperature measurements
At two nearby measuring stations water temperature was recorded every ten minutes (Fig. 1). To determine if oxygen was limited, samples of the surface water were taken and oxygen concentration was measured with a HQ20 Hach Portable LDOTM Dissolved Oxygen/pH Meter. Salinity was measured with a WTW-conductivity meter (Cond 3301) with a TetraCon®325 conductivity and temperature sensor. From the data of the measuring stations the mean daily water temperature during the monitoring period was calculated.

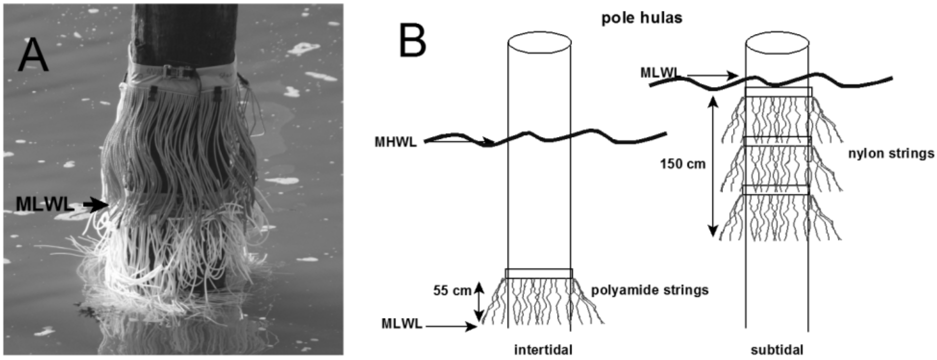

Figure 2 The pole hulas and their position in relation to the mean low water level (MLWL). MHWL = mean high water level.

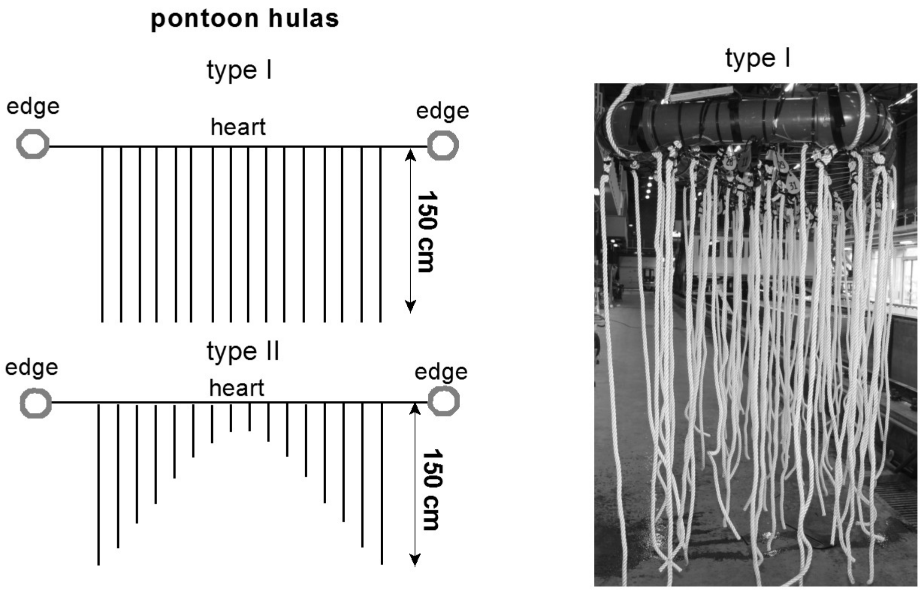

Figure 3 The pole two types of pontoon hulas.

Table 1 Properties of the pontoon hulas placed in the Scheurhaven and Pistoolhaven.

Location	Placing date	Pontoon hula	Number of ropes	n ropes m^{-2}	Length of ropes cm
Scheurhaven	16-03-2009	type I	208	64	150
Scheurhaven	16-03-2009	type II (bell type)	208	64	150–30
Pistoolhaven	17-03-2009	type I D64	168	64	150
Pistoolhaven	17-03-2009	type I D32	80	32	150
Pistoolhaven	17-03-2009	type I D16	40	16	150

Monitoring

The composition of the sessile community on the pole hulas was monitored monthly with the aid of an underwater camera. One set of monitoring strings was removed from each pole hula in June (107 days after placement) and October (231 days after placement) to determine wet biomass and species composition. However, in June strings were only removed from two hulas (out of seven) that were situated 100 cm below MLWL due to dangerous conditions. The strings with the fouling organisms were weighted on a scale with an accuracy of 1 gram after the surplus of water had dropped off. Wet biomass including that of shells (wet biomass = wet tissue plus calcimass) was calculated by extracting the weight of the strings in wet condition. Percentage coverage on the strings of dominant sessile species was estimated, while of other sessile species their numbers were counted. Due to the constant incoming and outgoing tugs it was impossible to sample mobile species on separate monitoring strings in an accurate way. Their abundance was estimated and a simple relative scale ranging from rare (1-10 individuals), common (11-100 individuals) to abundant (>100) was applied. All sessile species were identified to species level. For mobile species this was only done for samples taken in June. In October percentage coverage on reference poles was estimated as well. With the aid of a scrape net some of the fouling on the reference poles was removed and weighted after the surplus of water had dropped off. Wet biomass per m^2 at a 100 % coverage with mussels was calculated from a 100 % coverage of mussels within a frame of 20 cm x 20 cm.

Monitoring ropes on the pontoon hulas in the Scheurhaven were removed to determine wet biomass and species composition on May 19th, June 17th and July 24th 2009, respectively after 64, 93 and 130 days of exposure. The ropes with fouling organisms were weighted on location with a weighing hook with an accuracy of 5 gram hanging in a stable metal frame of 2 m high and 1 m wide. Wet biomass was calculated by extracting the weight of the ropes in wet condition. On July 24th 2009 percentage coverage of sessile species and abundance of mobile species was determined. All organisms were, if possible, identified to the species level. After analysis, ropes with fouling organisms were placed back to their original position. Measurements in the Pistoolhaven were executed on May 18th, June 18th, July 24th and November 6th 2009.

Calculating maximum biomass

Maximum biomass at a given time on each single rope in the absence of competition between ropes can be calculated by considering each individual rope with all the fouling species as one "organism". For this calculation laws of theoretical crop science are used (De Wit, 1960). This can be done by setting the reciprocal of the biomass per cm^2 pontoon hula (in this case multiplied by 100 for application within SPSS) against the reciprocal of the number of ropes per cm^2 per pontoon hula. The product ($\Omega * \beta$) of the intersection of the regression line with the *x*-axis and *y*-axis gives the maximum wet biomass per rope.

Statistical analysis

Statistical analysis was carried out with SPSS for Windows (Release 15.0). Linear regression was applied to test (a) the relation of wet biomass on the pole hulas and their position relative to the MLWL, (b) the relation of wet biomass production and rope density on the pontoon hulas in the Pistoolhaven, and (c) the relation of wet biomass on a pontoon hula rope in regard to its shortest distance to the edge of the hula

Analysis of covariance (ANCOVA)(covariate=shortest distance to the edge of the hula) was conducted to compare the wet biomass on the ropes on the pontoon hulas type I and in the Scheurhaven.

1-Way analysis of variance (1-way ANOVA) was applied to compare (a) the mean wet biomass on pontoon hulas with different rope densities in the Pistoolhaven and (b) the mean wet biomass on the ropes of the pontoon hula type I in the Scheurhaven with those of the pontoon hulas in the Pistoolhaven

Levene's test for the homogeneity of variances was applied for both ANCOVA and 1-way ANOVA.

Results

Abiotics

During the experiment oxygen content of the water fluctuated between 7.6 mg l^{-1} and 8.7 mg l^{-1} and salinity between 15 and 23. Water temperature varied from 7 °C at the start of the experiment in March, till 22 °C in mid August and then gradually dropped to 11 °C at the end of the experiment in November.

Succession

After placement in March pole hulas below MLWL were completely covered by diatoms within a month (solitary, stalked and colonial species). Above MLWL no macroscopic sessile organisms were observed. In the period between April and May some individuals of the sessile algae *Ulva lactuca* and *Porphyra umbilicalis* settled on the strings above MLWL, while the strings below MLWL were completely covered with a monoculture of the hydroid *Obelia dichotoma*. At the end of June more species were present (Table 2). Above MLWL the fouling community was dominated by *P. umbilicalis.* Below MLWL *O. dichotoma* was degenerating and was replaced by small individuals of the Blue mussel (*Mytilus edulis*) and the barnacle *Amphibalanus improvisus* (nn) (nn = not native). The number of seaweed species on the strings of pole hulas decreased from the MLWL downwards. In between the sessile organisms on the strings many mobile species were found (Table 3). Chironomidae, juvenile Polychaeta, crab larvae, the amphipod *Monocorophium insidiosum*, and the tanaidacean *Sinelobus stanfordi* (nn) appeared in high numbers. The amphipods *Monocorophium acherusicum, Microdeutopus gryllotalpa, Melita palmata* (nn) and the decapod *Hemigrapsus takanoi* (nn) were commonly found, while the amphipods *Caprella linearis*, *Caprella mutica* (nn), *Monocorophium sextonae* (nn), *Gammarus salinus*, *Hyale prevosti* and the gastropod *Crepidula fornicata* (nn) were only met on occasion.

At the end of October composition of the fouling community on the strings had changed considerably. Both above and below MLWL *P. umbilicalis* and *Ulva* species disappeared, while the red algae *Callithamnion roseum* and *Ceramium rubrum* increased considerably in abundance. On the whole *M. edulis* became the dominating species with an increasing abundance with depth, thereby outcompeting *A. improvisus*. The Blue mussel grew around the strings and because of the high number of strings were present in multiple layers. On several strings the ascidians *Styela clava* (nn) and *Molgula manhattensis* (nn) and the sponge *Halichondria panicea* were found. Despite a small spot of bryozoans, no fouling was found on the mussels. Mobile species were present between the sessile fauna in higher abundance in October than in June. The sea

Table 2 Coverage by seaweeds and sessile macrofauna of the monitoring strings of the pole hulas in the Scheurhaven on June 24th 2009 and October 26th 2009. >MLWL = above mean low water level. < MLWL = below mean low water level. avg = average. sd = standard deviation. max = maximum. min = minimum. bsw = brown seaweed. gsw = green seaweed. rsw = red seaweed. * non native.

position	sessile species	June 24th 2009						October 26th 2009					
		number of strings	times present	% coverage				number of strings	times present	% coverage			
				avg	sd	max	min			avg	sd	max	min
>MLWL	*Ulva lactuca (gsw)*	5	2	4.2	8.8	20	0	5	0				
	Ulva linza (gsw)	5	4	5.0	5.0	10	0	5	0				
	Porphyra umbilicalis (rsw)	5	5	11.0	10.8	30	5	5	0				
	Callithamnion roseum (rsw)	5	1	0.2	0.4	1	0	5	0				
	Ceramium rubrum (rsw)	5	0					5	1	0.2	0.4	1	0
	Mytilus edulis	5	0					5	5	5.2	3.2	10	1
	*Amphibalanus improvisus**	5	0					5	4	1.4	2.1	5	0
<MLWL	*Ulva lactuca (gsw)*	16	3	0.0	0.0	0.1	0	21	0				
	Ulva linza (gsw)	16	9	3.5	7.4	25	0	21	0				
	Porphyra umbilicalis (rsw)	16	6	8.6	10.3	25	0	21	0				
	Callithamnion roseum (rsw)	16	8	4.3	12.5	50	0	21	12	2.0	4.4	20	0
	Ceramium rubrum (rsw)	16	3	0.3	1.2	5	0	21	5	0.8	1.8	5	0
	Petalonia fascia (bsw)	16	1	0.0	0.0	0.01	0	21	0				
	Conopeum reticulum	16	1	0.0	0.0	0.1	0	21	0				
	Electra pilosa	16	4	0.0	0.1	0.1	0	21	0				
	*Ficopomatus enigmaticus**	16	0					21	1	0.1	0.4	1	0
	Halichondria panicea	16	0					21	9	0.6	1.2	5	0
	Botryllus schlosseri	16	1	0.1	0.4	1	0	21	0				
	*Molgula manhattensis**	16	0					21	2	0.6	1.0	2	0
	*Styela clava**	16	0					21	6	1.1	1.9	6	0
	Mytilus edulis	16	13	19.6	25.2	70	0	21	21	59.4	41.3	100	2
	Obelia dichotoma	16	12	13.8	11.9	30	0	21	12	0.4	0.5	1	0
	Sertularia cupressina	16	0					21	1	0.1	0.4	1	0
	*Amphibalanus improvisus**	16	16	13.0	11.5	40	0.01	21	19	2.2	2.3	10	0

star *Asterias rubens* and the prawn *Palaemonetes varians* were observed on many of the pole hulas below the MLWL. Also in October 2009 the Rock gunnel *Pholis gunnellus* was seen in-between the strings. Thicklip grey mullets (*Chelon labrosus*), a common fish in the port of Rotterdam were often foraging on the seaweeds from the pole hulas. On the poles underneath the pole hulas only barnacles with a coverage of 50% and occasionally a Blue mussel settled. Of these barnacles 80% was dead.
From April till October the same type of fouling developed on the reference poles below MLWL. In contrast with the strings *M. edulis* settled as one layer and on average covered the poles in October by some 50%. *A. improvisus* had an average coverage of 14%. A small amount of Pacific oyster spat was observed on the steel reference poles. In the zone of 50 cm above MLWL the reference poles were for 50% covered in codominance by the algae *P. umbilicalis*, *Ulva linza, U. lactuca* and *Blidingia minima*. In October *P. umbilicalis* disappeared and *U. lactuca* became the dominant species. *Fucus vesiculosus* was also found in low densities.
Succession on the pontoon hulas was similar to succession on the pole hulas with the exception that no seaweeds grew on the ropes of the pontoon hulas as a result of shading by the pontoons. In June 2009 composition of mobile species on the pontoon hulas resembled composition on the pole hulas, although Chironomidae and Polychaeta were rare. Young fish was regularly observed between the ropes, and on one occasion a young eel (*Anguilla anguilla*) was found between the mussels on a rope in the Pistoolhaven.

Table 3 Relative abundance of mobile macrofauna on the monitoring strings of the pole hulas in the Scheurhaven on June 24th 2009 and October 26th 2009. >MLWL = above mean low water level. < MLWL = below mean low water level.

position	mobile species	June 24th 2009	October 26th 2009
>MLWL	Amphipoda	common	common
<MLWL	Amphipoda	abundant	abundant
	Decapoda (crabs)	abundant	abundant
	Tanaidacea	abundant	abundant
	Chironomidae	abundant	rare
	Polychaeta	abundant	abundant

Biomass production on pole hulas

The amount of wet biomass (including shells) on the pole hulas increased significantly in regard to their position around MLWL in June and October (Fig. 4, $R^2=0.26$, $p<0.02$ and $R^2=0.42$, $p<0.001$). On all individual poles with hulas wet biomass was the lowest on the hulas between 0 cm and 50 cm below MLWL. On average wet biomass increased by a factor 2-3 with depth. There was a significant difference between the average wet biomass on the different poles with hulas ($F(6, 14)=3.86$, $p<0.02$) due to the fact that on two poles the coverage of the hulas with mussels was low compared with the others.

Total coverage on the reference poles with algae and macrofauna below MLWL varied between 50% and 100 % in October. *M. edulis* was the dominating species. Biomass mussels on pole hulas was estimated to be 4.4-11.4 times higher in regard to position below MLWL compared to mussel biomass on reference poles (Table 4).

Table 4 The wet biomass in g m^{-2} on the poles with hulas and the wet biomass in g m^{-2} on the reference (ref) poles without hulas at 100% coverage on the 26th of October 2009 in the Scheurhaven and its ratio.

	ref pole	pole with hulas					
		average (SE)		maximum		minimum	
position MLWL cm	wet biomass g m^{-2}	wet biomass g m^{-2}	ratio	wet biomass g m^{-2}	ratio	wet biomass g m^{-2}	ratio
0	9925	44006 (10266)	4.4	79477	8.0	8730	0.9
-50	9925	95092 (20591)	9.6	164115	16.5	19736	2.0
-100	9925	112996 (27368)	11.4	202677	20.4	16548	1.7

Biomass production on pontoon hulas

After settlement of *M. edulis* on the pontoon hulas in the Scheurhaven in June wet biomass on the ropes increased on average by a factor 16.1 (SD=3.5, max=24.0, min=10.3) for type I and 18.7 (SD=5.5, max=26.9, min=8.67) for type II. In July, a significant negative relation existed between the shortest distance of a rope to the edge of the pontoon hula and the biomass per cm rope (Fig. 5) The wet biomass of the bell type (II) pontoon hula was the highest per cm rope from the outside to the inside compared to the pontoon hula type I (ANCOVA, $F(1,45) = 6.16$, $p < 0.02$).

Wet biomass on the ropes of the pontoon hulas increased to a great extent after settlement of *M. edulis* in both harbour basins (Fig. 6). Within the pontoon hulas

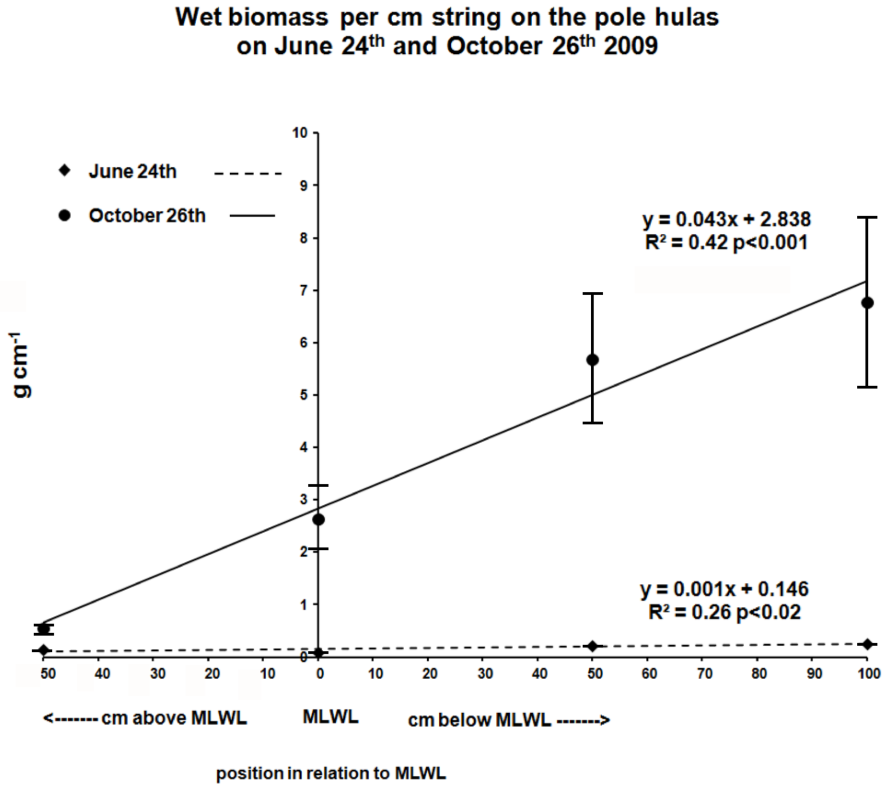

Figure 4 Relation between the average wet biomass cm^{-1}(± S.E.) on the string of the pole hulas in June and October 2009 from the Scheurhaven in relation to their position at the mean low water level (MLWL).

of the Pistoolhaven no relation was found between the position of a rope and the wet biomass per cm rope. However, wet biomass per cm rope was significantly different between the pontoon hulas in July and November (1-way ANOVA, $F(2,74) = 90.1$, $p < 0.001$ and $F(2,74) = 84.69$, $p < 0.001$, respectively) and negatively correlated with the number of ropes per m^2 ($R^2 = 0.60$, $p < 0.001$ and $R^2 = 0.67$, $p < 0.001$, respectively, Fig. 7). In November it was observed that with the hoisting of hulas D64 and D32 lumps of mussels that were attached to other mussels dropped from the ends of the ropes into the water. Furthermore on the ropes the density of mussels increased clearly towards the end of the ropes. On hula D16 the mussels were more evenly distributed over the ropes.

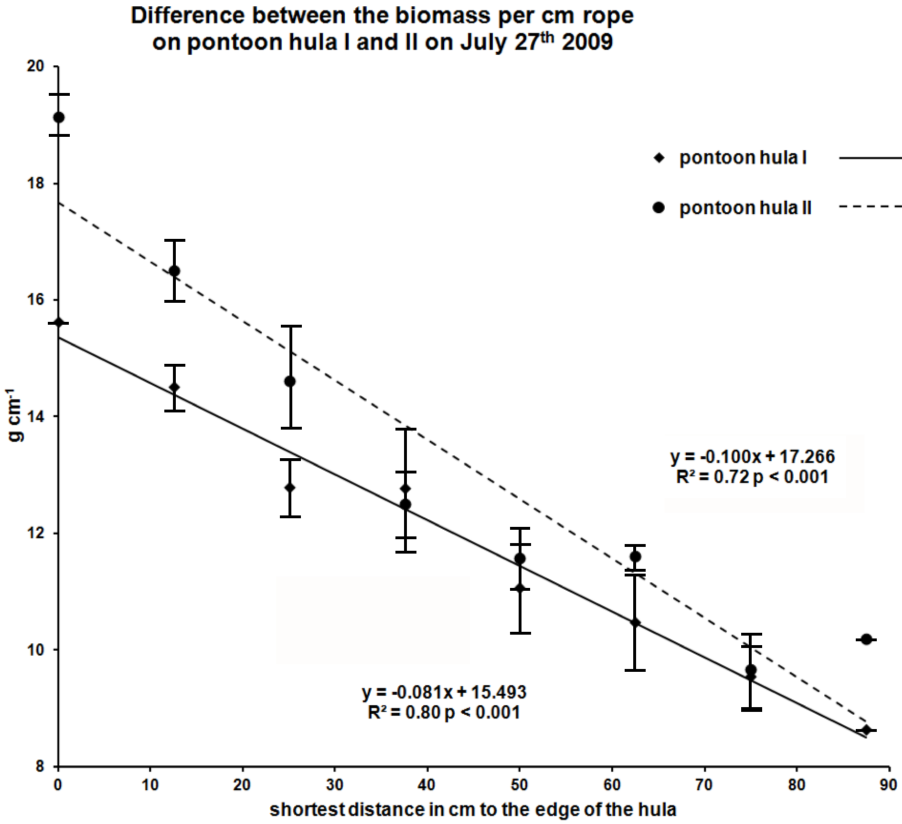

Figure 5 Relation between the average wet biomass cm^{-1} (± S.E.) on the ropes of pontoon hula I and pontoon hula II (bell shaped) from the Scheurhaven and the shortest distance of the ropes to the edge of the pontoon hula on July 24th 2009.

The average wet biomass (N=26, M=1796,8 g $rope^{-1}$, SE=67.2) on the ropes of pontoon hula type I from July in the Scheurhaven is compared with the average wet biomass on the ropes of the pontoon hulas D64 (N=27, M=607,2 g $rope^{-1}$, SE=33.0), D32 (N=24, M=842,1 g $rope^{-1}$, SE=42.6) and D16 (N=26, M=1382,1 g $rope^{-1}$, SE=50.3) from July in the Pistoolhaven. The average biomass on the ropes of pontoon hula I in the Scheurhaven was significantly higher (1-way ANOVA, $F(3,99)=116.79$, $p<0.001$).
For the sampling on November 6, 2009 in the Pistoolhaven using the laws of theoretical crop science (de Wit, 1960) the maximum biomass on one rope in the absence of competition between ropes would give a wet biomass of 3030 g $rope^{-1}$ (Fig. 8). This could be achieved at a density between 4 to 8 ropes per m^{-2}.

Figure 6 Pontoon hula type I D16 on July 24th 2009 in the Pistoolhaven.

Discussion

Species that settled on the pole hulas are commonly found in the Netherlands. A number of them are non-native. *M. manhattensis* (18th century) and *Amphibalanus improvisus* (19th century) invaded the Netherlands long ago as hull fouling, while others like *C. fornicata* (1926), *M. sextonae* (1952), *S. clava* (1974), *C. mutica* (1994) appeared in the course of the 20th century (Wolff, 2005, Cook et al., 2007). *H. takanoi* (2000)(Wolff, 2005) and *S. stanfordi* (2006)(van Haaren and Soors, 2009) were introduced recently in the first decade of this century.

The hydroid *O. dichotoma* was the first macroinvertebrate species that occupied the ropes of the pole (below MLWL) and pontoon hulas massively in early spring. This creates a great advantage for mussels as the larvae preferentially

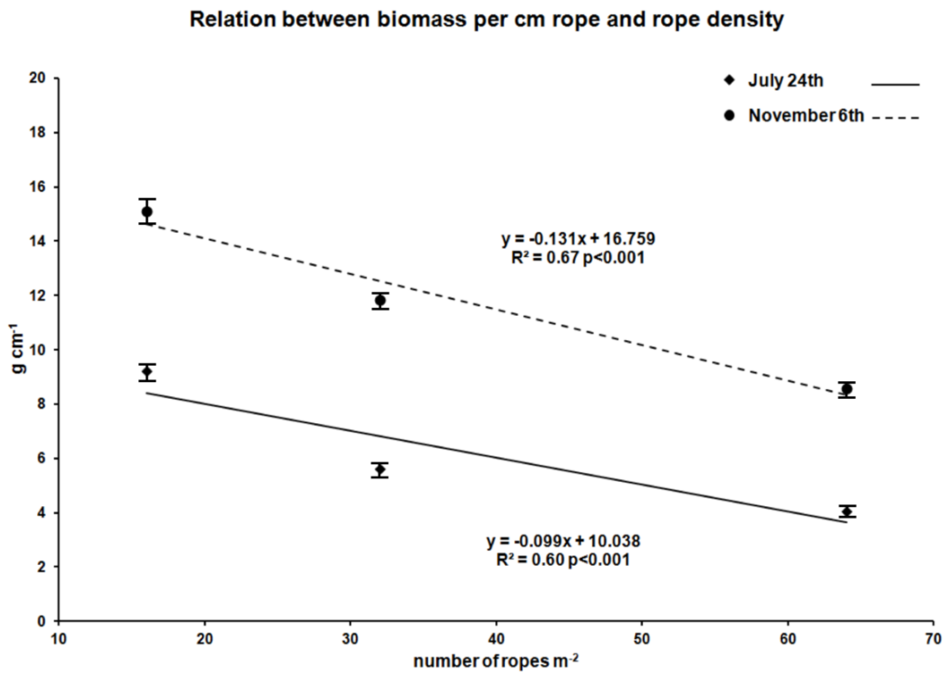

Figure 7 Relation between rope density and the average wet biomass cm^{-1} (± S.E.) on the ropes of the pontoon hulas from the Pistoolhaven on July 24^{th} 2009 and November 6^{th} 2009.

attach to filamentous substrates in particularly hydroids (Brienne, 1960, Pulfrich, 1996, Genzano et al., 2003).

Within the dense layer of *M. edulis* that developed in short time many mobile soft-bottom amphipods and young ragworms occurred in the interstices, which indicates sediment trapping. This phenomenon has been observed both in mussel culture on ropes (Loo and Rosenberg, 1983, Lopez-Jamar et al., 1984) and on suspended oyster cultures (Mazouni et al., 2001), but also in mussel beds (Dittmann, 1990, Crooks, 1998, Thiel and Ulrich, 2002, Koivisto and Westerbom, 2010). Within a harbour system where the top layer of the sea floor is continuously disturbed by the propellers of the ships, and where dredging is common practice, hula systems potentially offer a refugium for animals that normally inhabit soft sediments on the sea floor. From hanging mussel cultures it is known that if the infaunal macrobenthos community beneath rafts is depauperated the diet of fish is composed primarily of raft epifauna (López-Jamar et al., 1984). Furthermore, Iglesias (1981) found density and biomass of gobies to be higher in raft areas than in non-raft areas. The gobies were not supposed to take much advantages of the rope epifauna, but from the cover of the episubstrate of the shell deposits under the rafts (Chesney and Iglesias, 1979). Also crab density can be much higher in raft- areas compared to non-raft areas (Romero et al., 1982). Different bird species might well profit from an

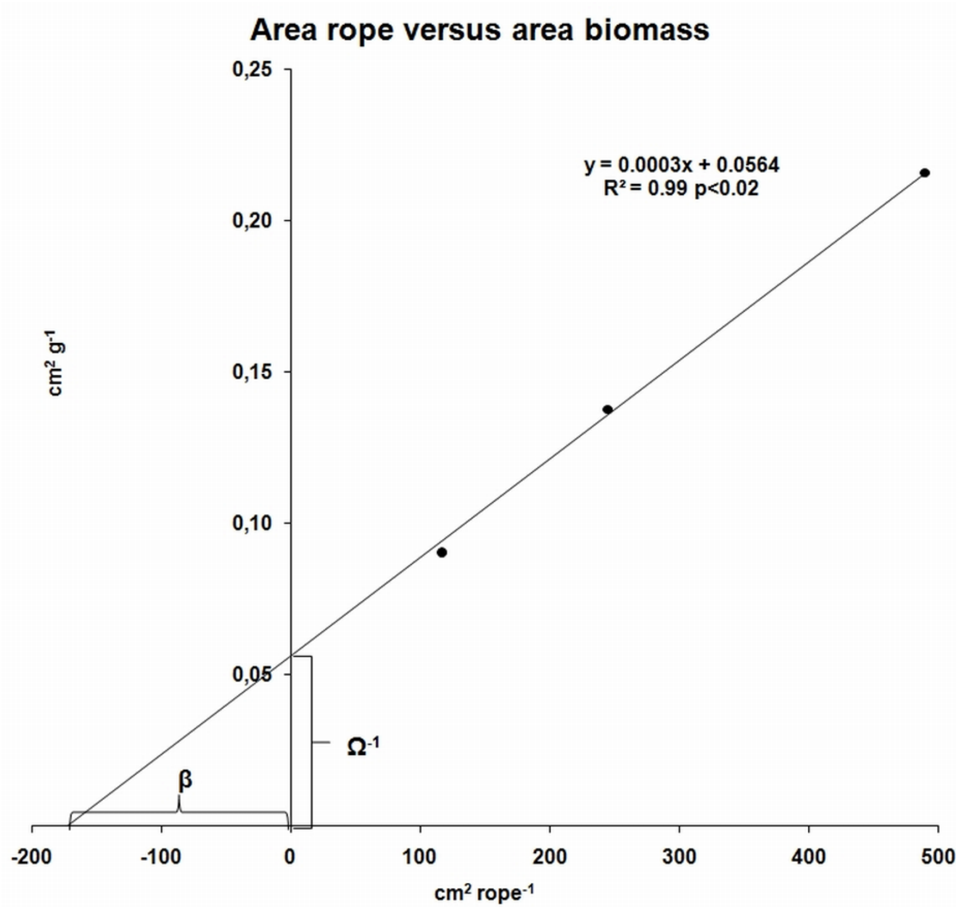

Figure 8 Relation between the area per gram wet biomass and the area per rope.

increase in density and biomass of the mussel. As clumps of mussels are released from the ropes due to heavy turbulence caused by propellers from time to time, these mussels may serve as the start of a mussel bed on the sea floor beneath piers and pontoons where pole and pontoon hulas are located and so creating new habitat.

The pole hulas above MLWL were mainly covered by large green and red seaweeds. No large brown seaweeds were found after one season. In the polyhaline harbours of the port of Rotterdam *F. vesiculosus* grows on anchor ropes and ropes that hold old car tires that serve as fenders. Applying pole hulas with thicker strings or ropes above the MLWL increases the biomass of large seaweeds from which not only the herbivorous Thicklip grey mullets will profit but many other fish species as well due to the presence of high numbers of amphipods.

The value of the pole hula to strengthen the biodiversity of the port seems (after one year) still limited, but they do increase the biodiversity on smooth concrete and steel poles by providing a more structure rich habitat enabling animals to creep in and between. An important phenomenon was the absence of the exotic *C. gigas* both on and on the pole under the strings of the pole hulas. Because of the inability of *C. gigas* to attach to relatively thin rope structures which prevented also direct settlement of *C. gigas* on the poles, the presence of pole hulas may strengthen the weakened position of *M. edulis* in the Rotterdam port area. In particular when pole hulas are introduced in March/April before spawning of *M. edulis* and *C. gigas,* because first spatfall in the Netherlands of *M. edulis* takes place in May/June (Tydeman, 1996) and *C. gigas* in July/August (Dankers et al., 2004), when water temperatures rises above 16 – 18 ºC.

The biomass on the pole hulas increased with increasing depth. Chaves and Chew (1975) have found that mussel spat settled less at the top metre of a rope and suggest that light intensity plays a role for settlement of spat. In the case of pole hulas the inundation duration as their position was around MLWL might have been important too. Due to the tidal movement more individuals could settle on the lower pole hulas and had more time to feed than on the higher ones. As the biomass (mainly *M. edulis*) per m^2 pole hula below MLWL was found to exceed the biomass per m^2 on a reference pole as much as 20 times, pole hulas are efficient tools in ecological engineering for strengthening the estuarine biomass production in harbours.

On both types of pontoon hulas in the Scheurhaven the biomass (mainly *M. edulis*) in July on the ropes decreased to a half from the edge to the heart of the hula demonstrating the limitation of food by competition. The competition on the bell shaped hula was slightly less because the individuals on the shorter ropes underwent less competition compared to those at the same location and on the same height within the hula with all ropes of the same length. This means that the horizontal food supply played a more important role in the competition than the vertical one. Also at the end of the ropes there is slightly more space to settle and less competition and this works in favour for the average biomass on shorter ropes.

No competition for food due to the location of the ropes within the pontoon hulas by means of the biomass on the ropes could be demonstrated in the Pistoolhaven. This is probably due to the size of the pontoon hulas in which the ropes on the inside still had a short distance to the edge of the pontoon hula. By varying the number of ropes a density dependent biomass production was shown. This means that the amount of food in the water column was limited. An additional aspect is that by the violent turbulence of the water by the propellers of ships the risk of rubbing against each other of the ropes increases at higher rope densities which cause the release of blue mussels and thus further limits the increase in biomass.

The higher biomass on the ropes of the pontoon hulas in the Scheurhaven in July compared with the biomass on the ropes of the pontoon hulas in the Pistoolhaven, could be the result of lower and stronger fluctuating salinity in the Pistoolhaven. Also the higher activity of ships near the pontoon hulas in the Scheurhaven will have caused more flow of water and hence provided a greater food supply.

Considering one rope on a pontoon hula as a single individual the maximum biomass on a rope in the absence of competition with other ropes at a certain moment has been calculated for the month November 2009, from the figure the optimal density for biomass production was estimated at 4 to 8 ropes m^{-2}. This is consistent with the findings of Brienne (1960) who found the best growth of mussels at a density of approximately 9 ropes m^{-2}.

Blue mussels filter their food together with inorganic silt out of the water column and excrete the remains as pseudofaeces. This has a positive impact on the transparency, which benefits algal growth and thus the oxygen concentration of the water. By the ingestion of large quantities of organic material from the water column the Blue mussel contributes to a rapid recirculation of nutrients and these are again used in the production of phytoplankton and benthic macroalgae (see Newell, 2004 for a comprehensive overview). Brzowowska et al. (2012) also showed that it is possible to improve seawater quality and attain high efficiency of removal of some heavy metals from raw seawater using the filtering activity of *Mytilus* sp. This would make easily moveable pontoon hulas suitable for quickly reducing the concentration of toxic substances in case of emergencies within a harbour before further distribution takes place.

Taking the above into account, ecological engineering in the port of Rotterdam with simple structures like pole hulas and pontoon hulas on a much larger scale could strongly enhance biological production and biodiversity and the water quality in the remains of the Rhine-Meuse estuary. This might have a positive impact on both the ecology of the rivers Rhine and Meuse and the North Sea. Furthermore it contributes to the ambition of the Rotterdam Port Authority to enhance the ecological value of the port wherever possible (Stuurgroep Regie Buitenruimte, 2004, De Wit et al., 2007).
In conclusion, succession on pole hulas above MLWL leads to a seaweed dominated community. Succession on pole hulas below MLWL and on pontoon hulas leads to a Blue mussel dominated community. Both pole hulas and pontoon hulas contribute to the bioproductivity and biodiversity of the polyhaline harbours of the port of Rotterdam. Pole hulas prevent settlement of the exotic Pacific oyster and this may strengthen the weakened position of the Blue mussel in the Rotterdam port area. Pole and pontoon hulas are successful tools for ecological engineering within harbours in the estuarine and marine environment.

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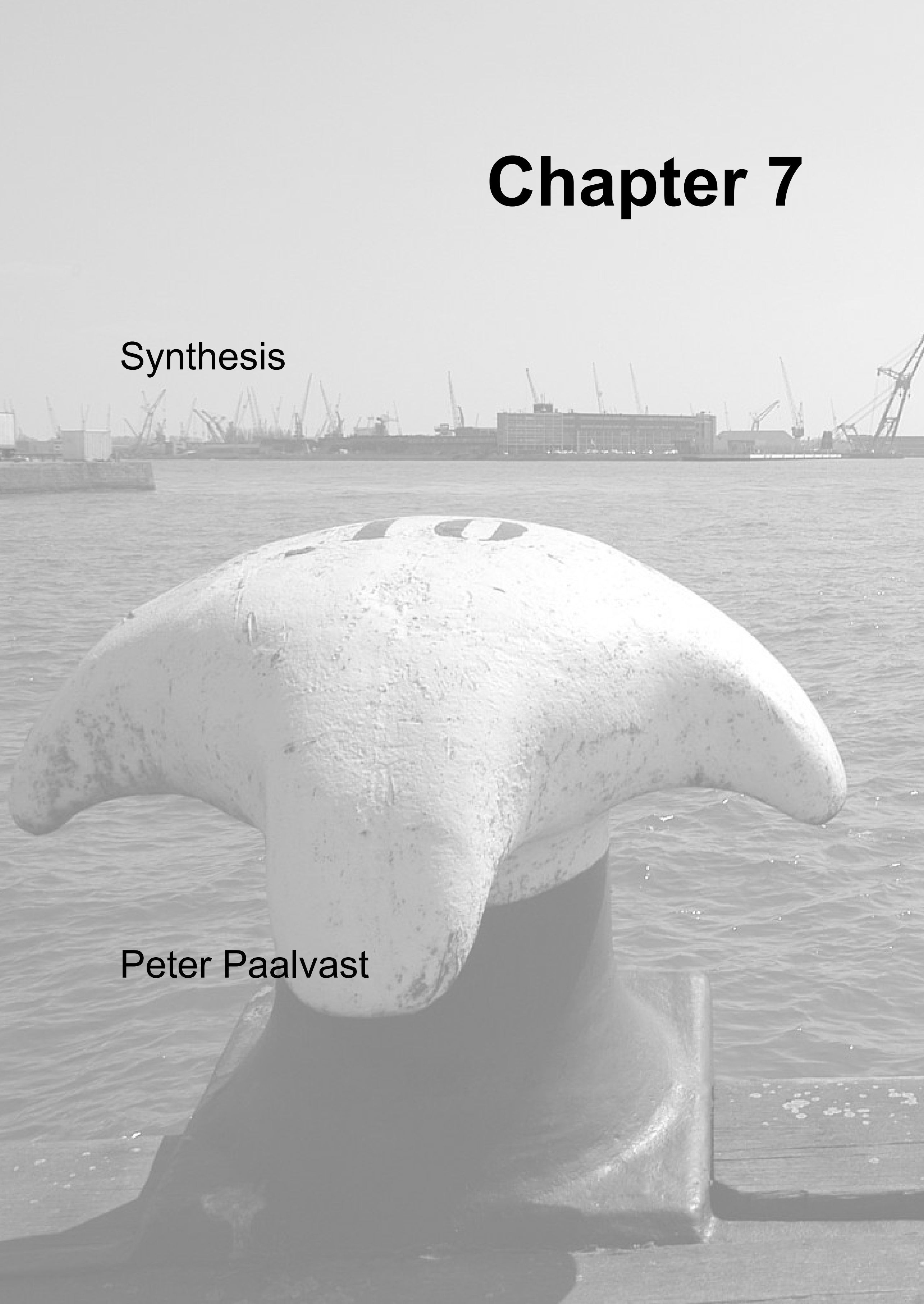
Chapter 7

Synthesis



Peter Paalvast

Broader perspective and developments elsewhere

Over the last two millennia the original estuarine area of the river Rhine and Meuse radically changed by natural processes such as sea level rise, sedimentation, erosion and vegetation development but in particular in the last century by infrastructural works as new waterways, damming, harbour construction and dredging leading to changes in tidal regimes and discharges of river water via the various distributaries (chapter 1).
The loss of the natural soft substrate intertidal ecotopes, the rise of hard substrate intertidal ecotopes (Fig. 1) and changes from natural to manmade estuarine waters during the 19^{th} and 20^{th} century in the area (the Noordrand) where the port of Rotterdam nowadays is situated are described in detail (chapter 2). Besides the impact of harbour extension and “improvement” of the rivers for navigation major morphological changes in the water systems in a few particular periods drastically affected the soft sediment ecotopes of the Noordrand. The excavation of the Nieuwe Waterweg and the disconnection of the Scheur from the Brielsche Maas together with the necessary land reclamation between 1868 and 1872 reduced the soft sediment estuarine area of the Brielsche Maas by 44%, of the Nieuwe Waterweg by 28% and that of the total area by 33% in just 4 years! However the closure of the Brielsche Maas in 1950 combined with the development of the Botlek harbour system was in fact the final blow for this part of the estuary and compared to 1835 less than 1% of the soft sediment estuarine ecotopes remained. With the development of Europoort and Maasvlakte 1 the last untouched dunes were wiped off the map.
Within the Noordrand due to human interventions over time the hydrology changed from one driven by the tides and river discharge to a hydrology that is controlled by man via the management of the Haringvliet sluices. The entire package of historical interventions has led to a significant increase in tidal range and a further penetration of the salt wedge land inwards (chapter 1).
In other European estuaries similar events took place. Large parts of the intertidal zone were reclaimed, ports developed exponentially in the 20^{th} century and deepening of the navigation channel for the ever growing vessels became common practice. A number of examples are discussed below.
In the Dutch-Belgian Westerschelde estuary between 1800 and 1995 the estuarine area (water surface included) dropped from some 450 km^2 to 310 km^2 by polderisation (Van der Weck, 2007). For navigation to mainly Antwerpen (Belgium) the navigation channel has been deepened several times. The historical changes in tidal range were the strongest 80 km stream upwards in the estuary near Antwerpen where the mean tidal range changed from 3.25 m in

1650 to 4.5 m in 1850 and 5.4 m in 2000 (Van den Berg et al., 1996, De Kramer, 2002).

In the Elbe-estuary most of the intertidal habitats were turned into land for agriculture before 1500 (DHBM, 1992). In the 20th century however 66% of the land outside the dikes, 11% of the intertidal zone and 27% of the shallow water area disappeared. The growth of the port of Hamburg and dredging for greater depth of the navigation channel led near Hamburg to an increase of the average tidal range from 1.8 m to 3.5 m between 1840 and 2000 with the highest increase between 1950 and 2000 (ARGE-ELBE, 2001).

In the Seine estuary the first embankments started in mid 19th century and at the end of that century the first works for the stabilization of the navigation channel started and continued until 1975 (Guézennec, 1999, Foussard et al., 2010). In 1834 the intertidal soft sediment zone of the Seine estuary near the mouth amounted 13,000 ha and this area has been reduced to 3,000 ha in 1985 (Avoine, 1981, Avoine, 1985) and to 2,900 ha in 1992 a total reduction of 78% (Avoine, 1995). There are no good time series of water levels in the Seine estuary, but due to the many human interventions in the Seine water system the low water level dropped 1.6 m at Rouen (120 km from the mouth, current tidal range approx. 2.2 m) and 1.0 m at Tancarville (20 km from the mouth, current tidal range approx. 6 m). The high water levels remained similar (data provided by GIP-Seine-Aval, Rouen, France). The volume of the estuary at high tide dropped from $1.6*10^9$ m^3 to $0.84*10^9$ m^3. As a consequence of all the interventions the penetration of the tide stream upwards was reduced and the turbidity zone and salinity limit of 0.5 moved 40 km downstream between 1955 and 1978 (Guillard and Romana, 1984). A particular phenomenon the “mascaret”, a tidal bore, is now no longer present in the estuary upstream le Havre, because of two large training walls on both sides of the navigation channel in the outer estuary (Avoine, 1995).

Within the Loire estuary the intertidal soft sediment habitats amounted 5,423 ha in 1821. Around 1992 64% of the intertidal zone had disappeared as a result of human activity (Migniot, 1997) such as port development, but also sand extractions upstream Nantes (Marion, 1998, Brière et al., 2010). The navigation channel was considerably deepened (from 10 m to 18 m near St-Nazaire) between 1980 and 2000 (Anonymous, 1984, Sogreah, 2006). Between the beginning and the end of the 20th century the tide influence upstream the Loire changed from 63 km to 105 km. Also the salinity front moved further upstream from 36 km in 1957 to 70 km in 1992 (Marion, 1998). The maximum tidal range changed at Nantes from 1881 from 2 m to 7 m in 1992!

To protect the infrastructural works such as harbours, quays and shores in the estuary a variety of hard substrates is used including wood. Today in the brackish and saline waters in the Netherlands only tropical hardwood is used. But no matter what type of hardwood is chosen it will be over time impaired to some degree by shipworm attacks (Koninklijk Instituut voor de Tropen, 1972).
The shipworm, *Teredo navalis*, a wood boring bivalve, has been found also recently in wooden panels in the Rotterdam port area (Fig. 1) in the harbours of Europoort and Maasvlakte 1, the Dintelhaven at the Hartelkanaal, the Berghaven at the Nieuwe Waterweg and at one occasion some 20 km upstream the mouth of the estuary in the Botlek harbour system (see Fig. 1, Chapter 3). It can be questioned if this shipworm has always been in the area, since its first appearance in this part of the Delta region in 1730 where nowadays the port of Rotterdam is situated. Several factors determine the shipworm to be able to establish and maintain. Crucial are salinity and water temperature. The shipworm thrives from a salinity of 10 and reproduces when the water temperature is higher than 11 to 12 ˚C. The optimum water temperature for the shipworm lies in the range of 15 ˚C and 25 ˚C. Between the end of April and the end of October the current water temperatures in the Rotterdam port area are in this range (Paalvast and Van der Velde, 2011) and it is unlikely that since its first appearance in the Dutch coastal waters temperatures would have been limiting. The historical isohalines that are presented in the introduction for 1907 and 1908 and before 1970 justify the conclusion that before 1970 the shipworm was unable to settle in Brielsche Maas, Nieuwe Waterweg, Scheur and Nieuwe Maas. A possible exception is the Berghaven at Hoek van Holland. Around 1970 Beer- and Calandkanaal and adjacent harbours (Europoort and Maasvlakte 1) were connected to the sea and the Nieuwe Waterweg, and turned into a large polyhaline area. From that moment, the shipworm had opportunities in the area to settle. Perhaps the animal was absent in the first 10 to 15 years after 1970 due to the severe pollution of river water and sediment, but especially after 1985 with the improved water quality it would have settled at first in driftwood and softwood pontoons. By weathering of many hardwood mooring poles and fenders made from basralokus and azobé, the shipworm also could settle therein. This is evidenced by the intense degree of shipworm infection in the outer three to five cm of the many hardwoods that were dragged out of the Beer- and Calandkanaal in recent years (personal observations by the author). Paalvast and Van der Velde (2011) suggested that *T. navalis* individuals drilling in hardwood in the port of Rotterdam need extra energy (chapter 3).
The average body length growth of first year shipworms in the Beer- and Calandkanaal in 2006 was twice as high as observed by Kristensen (1979) in the waters around Denmark. Such data are of particular interest in order to

estimate the potential damage that may inflict borers. The results of this study, in particular the rate of body length growth of the shipworm, have drawn the attention of archaeologists (Eriksen et al., 2013), that are deeply concerned about the expansion of the shipworm, *T. navalis*, in the southern Baltic Sea (Gregory, 2010). *T. navalis* has been spreading out from the western part of the Baltic since a penetration of salt water from the North Sea in 1993 (Manders and Luth, 2004). The fear is that this further expansion is the result of warming of sea water due to global climate change and that this could lead to a massive loss of unique archaeological shipwrecks (Bjordal et al., 2012). In the Baltic Sea around 100,000 shipwrecks are present of which at least 6,000 are of high archaeological value (Olsson, 2006). Climate change scenario simulations however show a future decrease in both surface and bottom salinity, a decrease that is mainly due to the expected increase in river run-off and a deepening of the permanent halocline (Krämer et al., 2013). So the expansion might be a temporary one once the salinity drops below survival limits as a result of more precipitation and higher river discharges, but by then many historical ships might have been destroyed completely.
Another location where several shipworm species, including *T. navalis*, are active is the Venice Lagoon. In the lagoon are about 22,000 wooden navigation marks (so called briccoles) and between 5,000 and 10,000 mooring poles that are threatened by shipworms (Ghirardini et al., 2010).
The evidence that in the port of Rotterdam area shipworms feed mainly on seston is provided by the stable isotope analysis (chapter 4). The results showed stable isotope values ($\delta^{13}C$, $\delta^{15}N$) for *T. navalis* that are similar to those of the filter feeders *Mytilus edulis* and *Crassostrea gigas*, which species were attached to the wood were the shipworm *T. navalis* was boring in. This is the first proof that the main food source of *T. navalis* is seston and that its presence in wood is for shelter (Fig. 1) rather than food in spite of symbiotic probably cellulolytic bacteria (Popham and Dickson, 1973).
Many old quays in the eastern part of the port of Rotterdam are build on fir and oak wood. Both types of wood can be easily destructed by *T. navalis*. At low river discharge, that mainly occur during summer, salinities at the bottom of the harbours reach values within the range for shipworm survival and growth (chapter 3). Damage of wooden structures in the eastern part of the port of Rotterdam might occur if low river discharges persist over time. Longer periods of low river discharges are predicted caused by future climate change. This creates possibilities for the shipworm to extend upstream in the port of Rotterdam area. This possible extension in the eastern part of the port of Rotterdam with increasing risk of damage is elaborated using four different climate scenarios (chapter 5, Fig. 1). Based on the low river discharges that

have occurred under the prevailing climate conditions with the associated salinity in the eastern harbour area, the risk of damage has been estimated in the order of once every 36 years. This seems a low risk but given the speed at which wooden foundations of quays may be affected by the shipworm, it might lead to serious damage. The worst case KNMI scenario (W^+) is an air temperature rise of 2 ˚C with a strong change in air circulation over Europe towards 2050 compared to 1990. Under this scenario the risk of damage increases to once every 3 years. However, even at no or just minor global warming, measures should be taken to protect vulnerable wooden constructions from shipworm attacks. Nowadays many harbours in the eastern part of the port of Rotterdam lose their function as the cargo is more and more handled at Maasvlakte 1 and 2 because of the growing size of ships. By shoaling of harbours that have fallen into disuse with sediment dredged elsewhere to a level at which the wooden foundations of the old quays are below the sediment bottom they can be protected from attacks by the shipworm.

The pollution of the port area, that reached the highest levels in the 1960s and 1970s, was not only the result of untreated discharges by industry in the area itself, but was primarily carried in by the Rhine from industrial, urban, agricultural and mining areas in the river catchment. The pollution of sediment and water was so severe that virtually nearly all life from the water disappeared. The heavily polluted harbour sludge was initially stored in dump sites along the Oude Maas, for which estuarine meadows, willow coppice and reed and rush beds were sacrificed. A large dump site is located on the territory of the city Vlaardingen with an area of nearly 600 hectares filled with a several metres thick layer of contaminated harbour sludge dumped in the period 1958-1970. Also, large quantities of heavily contaminated harbour sludge were dumped in the sea near the coast in the 1970s and 1980s. Partly due to protests from the environmental movement two large storage depots for contaminated harbour sludge were built on the Maasvlakte 1 called Slufter and Papegaaienbek (Fig. 11, chapter 1). In 2006 the harbour sludge (1.2 million m^3) of the Papegaaienbek was pumped to the Slufter. The policy of the port of Rotterdam, international collaboration and a stricter environmental legislation drastically reduced the pollution and most of the nowadays dredged harbour sludge can be discharged without much environmental risk at sea. The improvement of the aquatic environment after 1971 has led to the (re)colonisation of many species in the estuarine ecosystem of the Rotterdam port area and as a consequence biodiversity increased. The increase in biodiversity positively influences ecosystem services such as water quality and nutrient recirculation by filtration, shore protection due to wave attenuation by helophytes and other macrophytes, but also by sessile animals such as oysters and mussels in the sub- and intertidal zone. Recreation benefits by an increasing variety of birds that can be observed feeding in the harbours and along the shores and the increasing number of fish species has made the port of Rotterdam an important site for recreational fishing. However, there are also practical disadvantages such as the rapid fouling of pontoons and buoys that need more frequent cleaning. Amongst the flora and fauna that settled in the port of Rotterdam area are many invasive alien species. Some of them like the Japanese seaweed, *Sargassum muticum*, has not developed into a pest outcompeting native species as it does in many other locations where it has been introduced (Critchley et al., 1990), and might be considered in the Rotterdam port as habitat enrichment of the polyhaline harbours. Other species like the invasive Asian shore crab *Hemigrapsus takanoi* seems to replace the native Common shore crab, *Carcinus maenas*. Gollasch et al. (2008) summarises the introduced species in the North Sea region and their dominant introduction vectors. For the port of Rotterdam the main vectors are ship hulls and ballast water. Both the intake and discharge of ballast water in the port of Rotterdam still takes place without treatment although many steps are taken forwards to do treatment on a global basis (Gollasch et al., 2007, David and Gollasch, 2008, Tsolaki and Diamadopoulos, 2009). The port of Rotterdam is mainly a ballast water exporting port, with an intake more than twice as much from, than the discharge into the harbour system (Anonymus, 2008). Both intake (77.2 million m^3 per year) and discharge (34.8 million m^3 per year) quantities are considerable. For some harbours this means that on a yearly basis its total volume is used for the intake of ballast water and half of its volume for the discharge of ballast water.

The hard substrate and soft water bottom in the western part of the port of Rotterdam including the Botlek, the harbours of Vlaardingen and Maassluis and the river banks of Nieuwe Maas, Scheur and Nieuwe Waterweg below the high water level show a very low species richness because of daily and seasonal salinity fluctuations (personal observations). The hard substrate (Paalvast, 1998) and the soft sediment bottom (Crayemeersch et al., 1998) of the Beer- and Calandkanaal harbour system are much richer in species because of more stable high salinity conditions. The infra soft-bottom sublittoral benthic macroinvertebrate fauna however is unable to evolve to stable communities as the sea floor is continuously disturbed by dredging. To give an impression about the quantities involved, the sediment transport of the river Rhine towards the Noordrand is in the order of 3-4 million tonnes dry weight per year of which roughly half becomes deposited in the port, while the remainder is directly transported to the North Sea (Salomons, 2001).The amount of marine sediments entering the port, however, exceeds by far the contribution from the river which leads to a total amount of dredging of about 20 million m^3 per year. This means that almost 1 metre of the top layer of the whole sea floor of the Beer- and Calandkanaal harbour system is removed on a yearly basis.

The underwater environment of the port of Rotterdam is designed for harbour and industrial activities only. It is mainly made up of concrete and steel structures that stand perpendicular into the water column creating a dull monotonous environment. The fouling communities on these underwater structures in the polyhaline western part of the port of Rotterdam in 1998 were dominated by *Mytilus edulis*, the Blue mussel. From approximately that year *Crassostrea gigas*, the Pacific oyster, spread over the harbours and settled on all the hard substrate from subtidal to half way the intertidal zone, at the same time outcompeting the Blue mussel (Paalvast personal observations between 1995 and 2012). The Blue mussel is nowadays almost confined to a zone of about one metre around the low water level. The results of the pilot with the pole hulas (hula skirt like filamentous structures with 6 mm thick and 60 cm long strings attached around poles) and pontoon hulas (raft like structures with 15 mm thick and up to 150 cm long ropes) (chapter 6, Fig. 1), hanging in the water column as an enrichment of the underwater habitat, clearly showed that they can strengthen the weakened position of the Blue mussel in the port of Rotterdam. The Pacific oyster was unable to settle on the strings and ropes, and was also absent on poles on which hulas were attached. On both strings and ropes the Blue mussel developed in short time and was the dominating species with coverage rates of around 100% with a wet biomass of over 2 kg per m rope after four months of growth. Within these dense layers of blue mussels many mobile soft-bottom amphipods and young ragworms were found in the interstices that were filled with sediment. This shows that in harbour systems where the top layer of the sea floor is continuously disturbed by the propellers of ships, and where dredging is common practice, hula systems potentially offer a refugium for animals that normally inhabit the soft sediments on the sea floor. It also shows the potential of hula systems to improve biodiversity and increase bioproductivity from which the whole estuarine harbour ecosystem might benefit.

The article “Pole and pontoon hulas: an effective way of ecological engineering to increase productivity and biodiversity in the hard-substrate environment of the port of Rotterdam” has been noticed in China and Australia and the used method is considered also here as a possible innovative tool in harbour design for the mitigation of the loss of marine or estuarine nature (Ma et al., 2012, Grech et al., 2013). Hula like structures can also be applied in nutrient-enriched fresh water in combination with floating artificial reed beds and a pilot is currently underway in a UK reservoir (Mclaughlan and Aldridge, 2013).

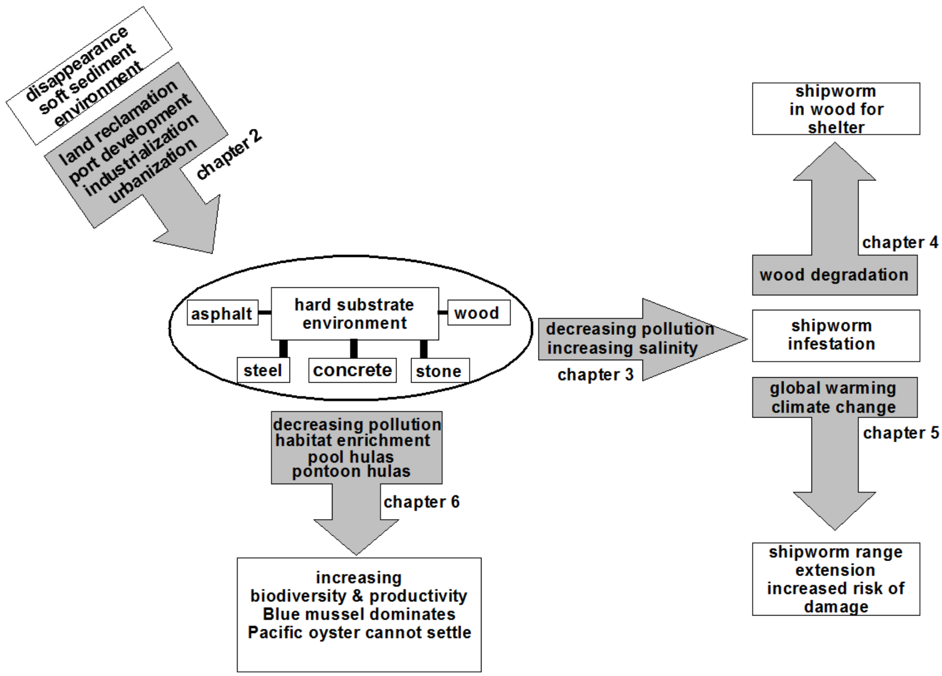


Figure 1 Main results of this study.

Future developments

Between 1980 and 2005, the water temperature at the bottom of the North Sea locally increased between 1 and 6 ˚C with direct effects on several fish species in a northward shift of their distribution or to greater depths (see Wiltshire and Manly, 2004, Perry et al., 2005, Marsh and Kent, 2006, Dulvy et al., 2008). This increase in water temperature also affects the distribution of marine borers. In the 1960s and 1970s *T. navalis* was the only shipworm species in the Tagus estuary. In 2009 *T. navalis* was no longer observed and was displaced by *Lyrodus pedicellatus* and *Nototeredo norvegica* (Borges et al., 2010). *L. pedicellatus* has already expanded northwards and has been found near Portsmouth in England. *L. pedicellatus* is active all year round (Murphy et al., 2009). It should not be ruled out that in the near future one of these species might settle in wood in the deeper parts of the polyhaline area of the port of Rotterdam, e.g. in the vicinity of the cooling water discharge area of the Maasvlakte power station.

From hell to haven: Improving the ecosystem of the port of Rotterdam

On the 2nd of October 2013 the port of Rotterdam, Rijkswaterstaat, the City of Rotterdam and the World Wildlife Fund signed an agreement to develop over a period of 10 years a nature friendly intertidal zone along the south bank of the Nieuwe Waterweg with a length of 5 km. Within this zone a brackish vegetation and intertidal sand and mud flat will develop over time. The total surface area accounts some 20 ha. This is only 0.4 percent of the 4,745 ha of soft estuarine intertidal ecotopes that existed around 1835 in the Noordrand, but this action might be a first step towards ecological restoration in this part of the Rhine-Meuse estuary. However, more measures can be taken along Scheur and Nieuwe Waterweg by overlaying the bare banks above high water with sediment in particular sand and so creating artificially a dune habitat for plants and associated fauna. Along the shores of the Scheur and Nieuwe Waterweg several small spots are present where sediment has been left or has accumulated and such communities developed (Paalvast, 1998, 2001).

As a measure to limit the risk of shipworm attacks the shoaling of harbours in the eastern part of the port of Rotterdam that have become in disuse, has been suggested above. The depth of these harbours can easily be reduced to about 2 m at low tide using dredged material from elsewhere in the harbour area (for example the Waalhaven). This will lower the channel detention of the area and thus the salt intrusion on the river. Disused quays that are in bad state can be demolished and turned into nature friendly tidal banks, so restoring gradients formerly common to estuaries. However economic activities do not allow shoaling of harbours and demolishing quays everywhere in the port of Rotterdam, but the pole and pontoon hula experiment demonstrated that with rather simple measures the ecosystem can be improved. Pole hulas can be easily attached to poles throughout the port of Rotterdam from the fresh and oligohaline waters in the eastern to the polyhaline waters in the western part creating a structure rich environment with a large surface for all sorts of algae and macroinvertebrate fauna to settle and grow. Other mobile macroinvertebrate fauna such as shrimps, prawns and crabs but also fish and diving water fowl will profit from the increase in primary and secondary production that structural enrichment and increase of intertidal and subtidal surface area will bring. If attaching hulas is not possible the floating pontoon hulas can be used. They have the great advantage to be moved in minutes without damaging the fouling organisms on the ropes when they interfere with shipping or harbour activities. Ideal places for pontoon hulas are the space underneath jetties and areas that are too shallow for ships. If no intertidal vegetation can be created, floating vegetation whether or not combined with hulas can be introduced with the same advantage of quick displacement or removal.

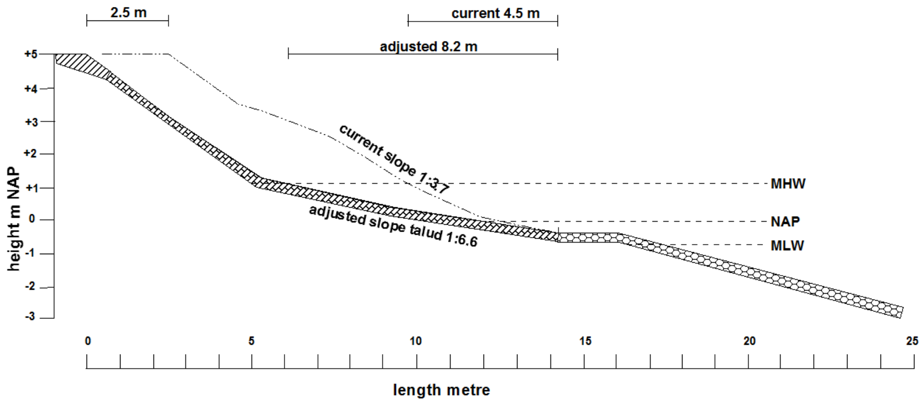


Figure 2 Example of adjusting the slope of a common type of retaining wall in the polyhaline harbours of the port of Rotterdam. MHW=mean high water level, MLW=mean low water level, NAP=Amsterdam Ordnance Datum. (after Paalvast, 1998).

In the polyhaline harbours Europoort and Maasvlakte 1 and 2 the primary production of large fucoid seaweeds can be highered (doubled or more) by dumping extra rip rap in the intertidal zone. The *Fucus vesiculosus* (Bladder wrack) vegetation is very important for intertidal amphipods where they hide and feed (Platvoet and Pinkster, 1995). These amphipods such as gammarids form a food source for fish and many seabirds. The total harbour shoreline length where the intertidal zone could be extended with extra rip rap is over 50 km. This could provide at least an extra 30 ha of seaweed vegetation, but also the slope of retaining walls can be made less steep enlarging the intertidal zone with up to 70% (Fig. 2). This has many advantages, such as extension and better development of the algal zones due to a less concentrated wave attack. In this way the hard substrate is better covered and the space between the stone pitching does not dry out, by which different organisms maintain themselves better. A flatter slope creates greater diversity and stability of the communities that are characteristic of hard substrates in the intertidal zone and have

therefore within the artificial harbour system higher values for nature than steep slopes.
There are also many variations possible in the way concrete, basalt or limestone blocks of the revetment of the slope of retaining walls can be placed that are washed twice a day by the tides. If revetment blocks are placed in an alternating manner (Fig. 3) the habitat of the eulittoral and supralittoral zone becomes more differentiated, sediment and organic material accumulates providing room to many more species compared to blocks placed in a uniform manner. Also the variation in type of blocks and space between them is crucial for determining biodiversity and productivity (Borsje et al., 2011).

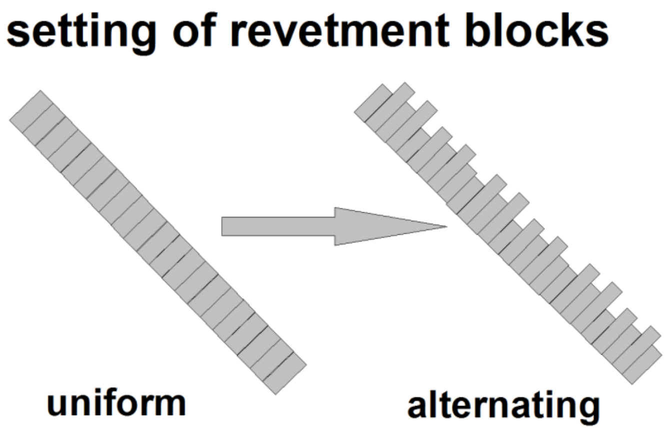


Figure 3 Setting revetment blocks in an alternating manner to create a more differentiated habitat on the slope of retaining walls.

Paalvast (1998, 2005) proposed the creation of artificial tide pools in the eulittoral zone of Beer- and Calandkanaal. In 2011 the first artificial tide pools were constructed despite the warning of the author that they were built at a location that was characterized by heavy sedimentation of sand. The argument to construct the tide pools anyway was motivated by the fact that the computer model did not show any significant sedimentation. Within a few months the pools were completely filled with sand. This proves once again that the results of model calculations should be compared with the experience gained in the field and that computer models alone form a weak base for nature development.
Quays are constructed for the mooring of vessels that should not be hampered by structures to improve the ecosystem. With simple measures much improvement in structure richness can be gained within the space below many of the quays. However, roughening of concrete subtidally as a measure to

improve structure richness, apart from hulas, is useless as within a short period of time the fouling organisms themselves and their remains (dead barnacles, shells of oysters) turn the smooth concrete into a rough layer. The same accounts for the intertidal zone of perpendicular concrete quays. An experiment in a polyhaline harbour of the port of Rotterdam with concrete slabs with holes, slits and rough structure to improve biodiversity and production did not show any improvement in fouling compared with smooth concrete (Paalvast, 2010). In all cases the fouling community consisted of a thin layer of small green algae and barnacles in low densities. The main reason for the poor development is the long low water period of about 8 hours causing the fouling community to dry out completely. Only a few species withstand these conditions. More success is to be expected of larger open structures in quay walls around mean low water where communities do not dry out because of the lapping of the water (see Paalvast, 1998).

When the above mentioned possibilities for the improvement of biodiversity and productivity are carried out, the port of Rotterdam might become a haven for estuarine nature!

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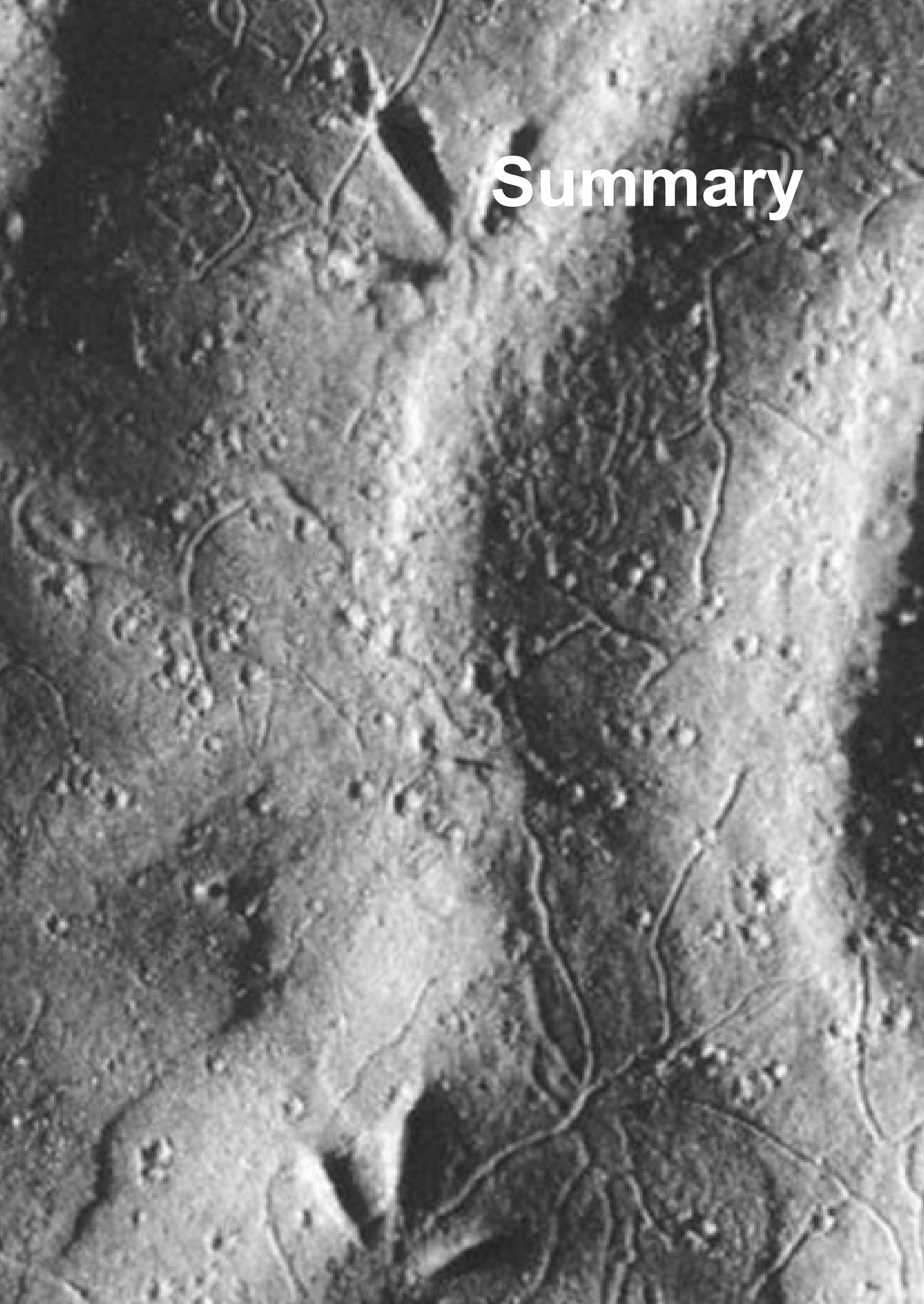
Summary



Virtually every square metre of the Netherlands has been turned over by the hands of man changing the natural dynamic landscape into a typical Dutch cultural landscape of polders, dikes, restrained rivers, closed estuaries, et cetera. A part of the Netherlands that has been altered strongly is the port of Rotterdam area in the south west of the Netherlands including nowadays the Rhine-Meuse estuary (chapter 2). With the growth of the port of Rotterdam the now so-called Noordrand, comprising the tidal rivers Brielsche Maas, Botlek, Scheur, Nieuwe Waterweg and Nieuwe Maas was turned from a soft sediment environment into a hard substrate one. Around 1835 these tidal rivers were characterised by soft substrate ecotopes as reed and rush beds, tidal willow coppice (grienden in Dutch), estuarine meadows, sand and mud flats, beaches and dunes. Hard substrate was mainly found in the harbours along the Nieuwe Maas as quay walls. The total estuarine area of the Noordrand around 1835 measured 8,375 ha, 3,543 ha of tidal river, 74 ha of tidal harbour, 4,745 of soft substrate ecotopes and only 16 ha of intertidal hard substrate ecotopes. Between 1835 and 1880 the area of the port of Rotterdam grew slightly to 90 ha, but the total estuarine area shrunk by 19% mainly by the disappearance of more than half of the area of soft estuarine ecotopes by land reclamation related to the excavation of the Nieuwe Waterweg and river training works along the Nieuwe Maas. The hard intertidal substrate ecotopes, shore defences, quay walls, piers and groynes doubled to 32 ha. From 1880 till WWII (1940) the port surface extended from 90 ha to 750 ha and the hard intertidal substrate increased accordingly to 95 ha. After the WWII till 1970 the port of Rotterdam itself underwent an enormous growth to almost 4,000 ha. Because of the closure of the Brielsche Maas, the development of the Botlek, Europoort and Maasvlakte I harbour systems the soft estuarine ecotopes were reduced to 17 ha, less than 4 ‰ of the 4,745 ha in 1835. The tidal river area decreased also by 30% due to the loss of the Brielsche Maas. The intertidal hard substrate on the other hand increased from 95 ha around 1940 till 338 ha in 1970. The shoreline of the Noordrand consisted in 2008 of 344 km of hard substrate and only 1 km of soft substrate. Nowadays this part of the Rhine-Meuse estuary can be considered as completely petrified. Within the Noordrand due to human interventions over time the hydrology changed from one driven by the tides and river discharge to a hydrology that is controlled to a great extend by man via the management of the Haringvliet sluices. The entire package of historical interventions has led to a significant increase in tidal range and a further penetration of the salt wedge land inwards.

The demolishing of wooden constructions (quay walls, sluices, dike defences) by the shipworm (*Teredo navalis*) in the 18th century was in fact the onset for the

petrification of the estuary. It is nonetheless very unlikely that the shipworm after its first appearance in 1730 in the Dutch coastal waters could have been present in the Noordrand (chapter 7). The construction of Europoort and Maasvlakte I however created salinity conditions for the shipworm to settle. Until 2003 nothing was known about the presence of the shipworm in the port of Rotterdam area. With the aid of wooden panels between 2004 and 2008 the distribution of the first year shipworms, settlement, growth and the degree of damage has been studied (chapter 3). The shipworms were found all over the western polyhaline harbours (Beer- and Calandkanaal) and on occasion in harbours nearby that showed large seasonal and daily fluctuations in salinity. In 2006 the shipworm was found in fir panels 20 km upstream from the polyhaline harbours in the Botlek, demonstrating their ability to travel with the tidal currents over considerable distances and to settle once the abiotic conditions become favourable. In the first season after settlement they showed a substantial body length growth rate of 0.18 cm day^{-1} in 2006. The longest shipworm found was in 2006 and measured 36.8 cm after 4-5 months of growth after settlement. The maximum damage consisted of the disappearance of 12.4 % of the wood of a fir panel in 4-5 months after settlement.
The question arose, “What is the main food source of the shipworm *T. navalis*?”. Does the shipworm feeds on wood or on seston filtered from the water column? The question has been approached by stable isotope analysis of soft bodies of the shipworm, *Mytilus edulis* (Blue mussel) and *Crassostrea gigas* (Pacific oyster) both known as filter feeders and attached to the same wood as the shipworm was boring in (chapter 4). It was demonstrated that the shipworm *T. navalis* is mainly feeding on seston by filter feeding instead of by wood consumption. *T. navalis* showed similar stable isotope values ($\delta^{13}C$, $\delta^{15}N$) as *M. edulis* and *C. gigas*.
Based on water temperature data between 2003 and 2008 it is clear that the shipworm could have performed its boring activity 94% of the time year round. The historical river discharges of the Rhine indicate that the shipworm could have settled once in 36 years for a short period of time in the eastern part of the port of Rotterdam where digestible wood underneath quays is available (chapter 3). This threw up new questions, “Will climate change by global warming affect the distribution of the shipworm in the port of Rotterdam area?” and “Will climate change by global warming increase the risk of damage of vulnerable structures by the shipworm?”. Both questions were answered by applying the effects of four climate change scenarios for the Netherlands on river discharge and salt intrusion (chapter 5). Global warming will cause dry and warmer summers and decreased river discharges. Lower river discharges lead to an extension of the salinity gradient in upstream direction in summer. As a consequence of this the

shipworm might expand its distribution stream upwards and attack wooden structures. Scenarios with a temperature increase of one and two degrees Celsius by 2050 compared to 1990 with a weak change in air circulation above Europe will lead to an increased chance of shipworm damage upstream 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 expansion of the shipworm stream upwards will also be manifest in other Northwest European estuaries and will even be stronger in Southern Europe.

The reduction of the severe pollution created chances for many plant and animal species to settle in the ports' aquatic environment. However the underwater environment is designed for harbour activities only. With a pilot study (chapter 6) with hanging underwater structures made of strings (6 mm thick and 55 cm long) and ropes (12 mm thick and 150 cm long), respectively called 'pole hulas' and 'pontoon hulas', it was shown that biodiversity and production could significantly be improved in the polyhaline harbours. Pole hulas (hula skirt like structures) were attached to mooring poles, while pontoon hulas (raft like structures) were placed in the open space of mooring pontoons. Both structures were rapidly colonized by a variety of organisms. *M. edulis* was the dominating species after a few months. In the dense layer of *M. edulis* on both pole hulas and pontoon hulas many mobile soft-bottom amphipods and young ragworms occurred, demonstrating that colonisation on these structures compensates for biodiversity loss of bottom fauna due to dredging and disturbance by propellers of ships. No settlement of the exotic *C. gigas* was observed on the strings of the pole hulas, the ropes of the pontoon hulas and not on poles with hulas. This oyster has colonised the western part of the Rotterdam port probably since the 1990s. The wet biomass of blue mussels (including shells) on pole hulas was found to be positively correlated with depth and was between 4.4-11.4 times higher compared to biomass on reference poles. Biomass production on the ropes of pontoon hulas was density dependent, and optimal density of ropes was estimated at 4 to 8 ropes m^{-2}. Also limitation of food by competition was shown as biomass (mainly *M. edulis*) on ropes of pontoon hulas decreased to a half from the edge to the heart of the hula. The experiment proved that ecological engineering in the port of Rotterdam with simple structures such as pole and pontoon hulas strongly enhances sessile biological production and biodiversity, that is likely to have a positive impact on local water quality, and, if applied at larger scales, positive influences the ecosystem in the remains of Rhine-Meuse estuary.

In the synthesis (chapter 7) the results of this study are placed in a broader perspective and compared with developments elsewhere. Soft sediment ecotope losses occurred in most large western European estuaries, and tidal ranges and lengths of salinity gradients changed dramatically in the last two centuries. Worldwide, there are concerns about the range expansion of shipworms related to global warming and many studies are carried out to prevent shipworm damage. The pole and pontoon hula experiment has been recognized as an innovative tool for the improvement of the habitat of harbours. More simple measures are described that could help to turn the port of Rotterdam in the direction of a haven for estuarine nature.

Samenvatting

Vrijwel elke vierkante meter van Nederland is wel door de mens op de schop genomen waardoor het natuurlijke dynamische landschap is veranderd in een typisch Nederlands cultuurlandschap van polders, dijken, beteugelde rivieren, afgesloten zeearmen, enzovoorts. Een deel van Nederland dat het sterkst door de mens is veranderd, is wel het Rotterdamse havengebied in het zuidwesten van Nederland dat tegenwoordig het belangrijkste deel van het Rijn-Maasestuarium omvat (hoofdstuk 2). Met de groei van de haven van Rotterdam is het gebied, dat nu de Noordrand wordt genoemd en de getijdenrivieren Brielsche Maas, Botlek, Scheur, Nieuwe Waterweg en Nieuwe Maas omvatte, veranderd van een omgeving van zachte substraten in een die gedomineerd wordt door hard substraat. Rond 1835 werden deze getijdenrivieren gekarakteriseerd door ecotopen van het zachte substraat zoals riet- en biezenvelden, grienden, grasgorzen, zand- en slikplaten, stranden en duinen. Hard substraat werd nagenoeg alleen gevonden in de havens langs de Nieuwe Maas in de vorm van kademuren. Het totale estuariene oppervlak van de Noordrand bedroeg toen 8375 ha, verdeeld in 3543 ha getijdenrivier, 74 ha getijdenhavens, 4745 ha aan zachtsubstraatecotopen en slechts 16 ha aan hardsubstraatgetijdengebied. Tussen 1835 en 1880 groeide het (natte) oppervlak van het Rotterdamse havengebied slechts licht tot 90 ha, maar het totale estuariene oppervlak kromp met 19%, voornamelijk door het verdwijnen van meer dan de helft van het areaal van zachtsubstraatecotopen door de aanleg van de Nieuwe Waterweg en rivierregulatiewerken langs de Nieuwe Maas. Het harde getijdensubstraat, zoals oeververdedigingen, kademuren, pieren en kribben verdubbelde tot 32 ha. Vanaf 1880 tot aan de Tweede Wereldoorlog (WWII) (1940) breidde het havenoppervlak zich uit van 90 ha tot 750 ha en het harde getijdensubstraat tot 95 ha. Na WWII onderging de haven een enorme groei tot bijna 4000 ha in 1970. Door het afsluiten van de Brielsche Maas en de ontwikkeling van de haven- en industriegebieden Botlek, Europoort en Maasvlakte I werd het areaal zacht estuarien substraat gereduceerd tot 17 ha, minder dan 4‰ van de 4745 ha in 1835. Het getijdenrivieroppervlak nam af met 30% door het verlies van de Brielsche Maas. Het harde getijdensubstraat daarentegen nam tussen 1940 en 1970 toe van 95 ha tot 338 ha. De oeverlijn van de Noordrand bestond in 2008 voor 344 km uit hard en voor 1 km uit zacht substraat. In de Noordrand is ten gevolge van ingrepen door de mens in de loop der tijd de door de getijden en rivierafvoer bepaalde hydrologie voor een groot deel veranderd in een hydrologie die in sterke mate wordt bepaald door de sturing met de Haringvlietsluizen.

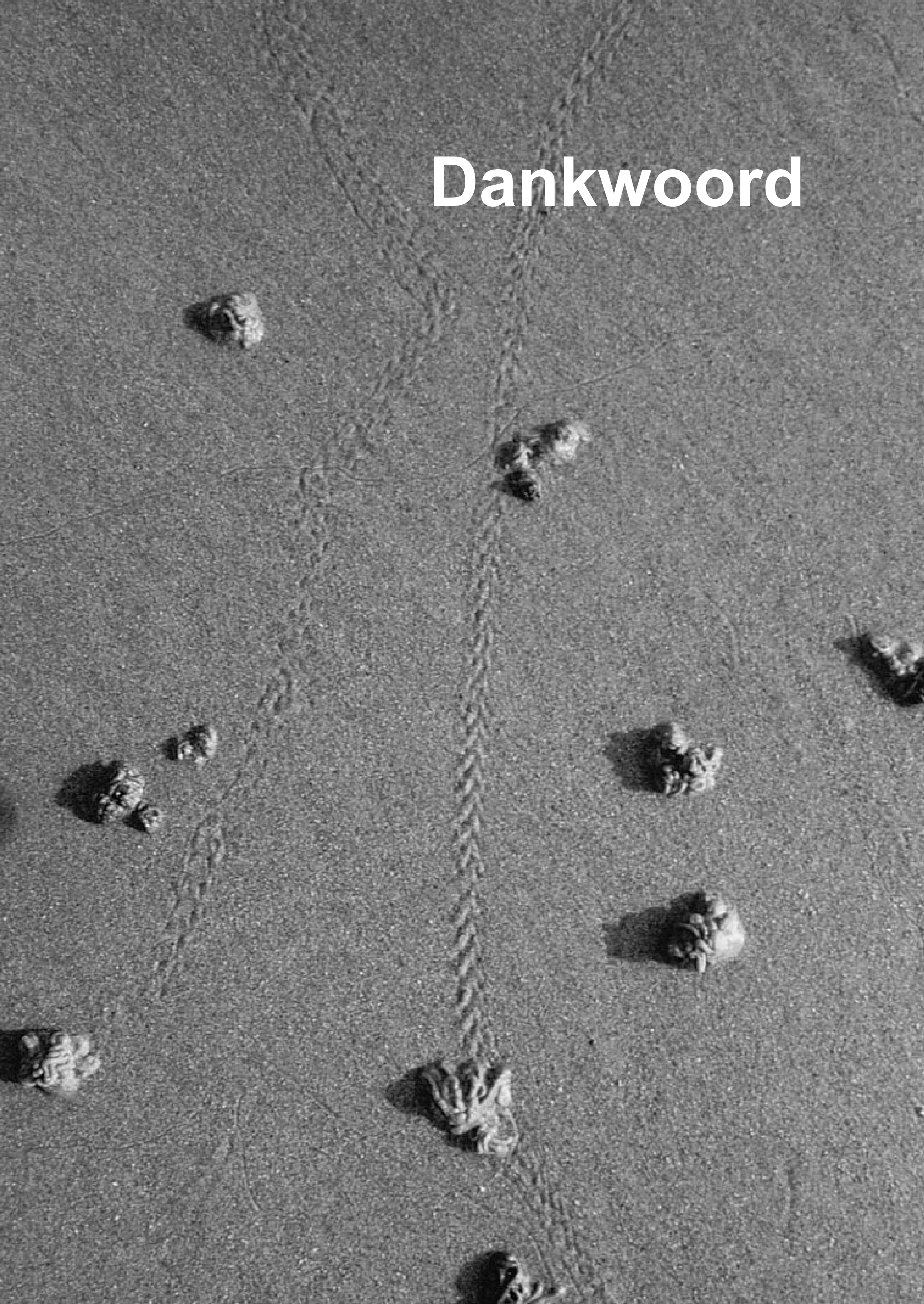
De enorme schade die in de 18de eeuw door de paalworm (*Teredo navalis*) aan houten constructies werd aangericht, is de aanleiding geweest om steeds meer steen te gaan gebruiken. Het is twijfelachtig of de paalworm na zijn eerste verschijning in 1730 in de Nederlandse kustwateren, in wat nu de Noordrand is, aanwezig is geweest (hoofdstuk 7). De aanleg van Europoort en Maasvlakte I hebben echter saliniteitscondities gecreëerd die gunstig zijn voor de paalworm om zich te vestigen. Tot 2003 was er niets bekend over de aanwezigheid van de paalworm in het Rotterdamse havengebied. Tussen 2004 en 2008 is met behulp van houten testplankjes de verspreiding, vestiging, groei en de mate van schade van eerstejaarspaalwormen bestudeerd (hoofdstuk 3). De paalwormen werden gevonden in de westelijke polyhaliene havens (Beer- en Calandkanaal) en zo nu en dan in nabijgelegen havens met een dagelijkse en jaarlijkse fluctuatie in het zoutgehalte. In 2006 werden paalwormen in vurenhouten testplankjes 20 km stroomopwaarts van de grote polyhaliene havens in de Botlek gevonden. Dit toont aan dat ze in staat zijn zich met de getijdenstromen over aanzienlijke afstanden in het estuarium te verplaatsen, en zich te vestigen als de abiotische condities dat toelaten. In het eerste seizoen na vestiging in 2006 vertoonden de paalwormen een lichaamslengtegroei van 0,18 cm per dag van het lichaam. De langste paalworm werd gevonden in 2006 die na een groeiperiode van 4-5 maanden na vestiging een lengte van 36,8 cm had bereikt. De maximale schade bestond uit het verdwijnen van 12,4% van het hout van een testplank binnen een periode van 4-5 maanden na vestiging.
De vraag rees, “Wat is de hoofdvoedselbron van de paalworm, *T. navalis*?”, “Leeft de paalworm van hout of van seston gefilterd uit de waterkolom?”. De vraag is beantwoord door stabiele isotopenanalyse van het lichaam van de paalworm en van *Mytilus edulis* (Gewone mossel) en van *Crassostrea gigas* (Japanse oester), filtreerders die op het hout zaten waar de paalworm zich had ingeboord (hoofdstuk 4). Er kon worden aangetoond dat de paalworm, *T. navalis*, zich hoofdzakelijk voedt met seston door filter feeding. *T. navalis* vertoonde dezelfde stabiele isotoopwaarden ($\delta^{13}C$, $\delta^{15}N$) als *M. edulis* en *C. gigas*.
Op basis van de gemeten watertemperaturen tussen 2003 en 2008 werd het duidelijk dat de paalworm 94% van de tijd zijn booractiviteit heeft kunnen uitoefenen. Het verloop van de historische rivierafvoeren van de Rijn (1901 t/m 2008) laat zien dat de paalworm zich een keer in de 36 jaar in het westelijk havengebied, waar voor de paalworm kwetsbaar hout aanwezig is, zou hebben kunnen vestigen (hoofdstuk 3). Dit riep de volgende vragen op, “Heeft klimaatsverandering door stijging van de luchttemperatuur gevolgen voor de verspreiding van de paalworm in het Rotterdamse havengebied?” en “Wordt door klimaatsverandering door stijging van de luchttemperatuur de kans groter

dat kwetsbare structuren door de paalworm worden aangetast?”. Beide vragen zijn beantwoord door de effecten van vier klimaatveranderingscenario’s voor Nederland toe te passen op rivierafvoer en zoutindringing (hoofdstuk 5). Wereldwijde luchttemperatuurstijging veroorzaakt droge en warmere zomers en verlaagde rivierafvoer. Verlaagde rivierafvoer leidt tot een verdere stroomopwaartse zoutindringing in de zomer. Een gevolg hiervan is dat de paalworm zijn verspreiding stroomopwaarts kan uitbreiden en houten structuren kan aantasten. Klimaatveranderingscenario’s met een temperatuurstijging van een of twee graden Celsius tegen 2050 vergeleken met 1990 met een zwakke verandering in de luchtcirculatie boven Europa zullen leiden tot een toename van de kans op paalwormschade tot respectievelijk eens in de 27 en 22 jaar. Echter bij sterke verandering van de luchtcirculatie boven Europa, neemt de kans toe tot respectievelijk eens in de 6 en 3 jaar. De uitbreiding van de paalworm stroomopwaarts zal zich ook in andere Noordwest-Europese estuaria voordoen en mogelijk nog nadrukkelijker in Zuid-Europa.

De afname van de ernstige waterverontreiniging heeft kansen gecreëerd voor de vestiging van vele planten- en diersoorten in het aquatische milieu van de Rotterdamse haven. De ruimte onder water is echter alleen voor havenactiviteiten ingericht. In een pilotstudie (hoofdstuk 6) met onderwater-hangende substraten gemaakt van touwtjes (6 mm dik en 55 cm lang) en touwen (12 mm dik en 150 cm lang), respectievelijk paalhula’s en pontonhula's genoemd, is aangetoond dat deze de biodiversiteit en bioproductie in de polyhaliene havens significant kunnen verhogen. Paalhula's (op Hawaiiaanse rokjes lijkende structuren) werden rond palen gebonden, terwijl de pontonhula's (drijvende structuren met daaronder aan een netwerk hangende touwen) in de open ruimte van pontons werden geplaatst. Beide touwstructuren werden binnen zeer korte tijd door een variatie aan organismen gekoloniseerd. *M. edulis* was na een paar maanden de dominante soort. In de dichte laag mosselen kwamen veel vlokreeftachtigen en borstelwormen van de zachte waterbodem voor. Dit toonde aan dat de kolonisatie van deze structuren compenseert voor de afname in biodiversiteit van het macrozoöbenthos van de zachte waterbodem ten gevolge van baggeren en omwoeling door sterke waterstroming veroorzaakt door scheepsschroeven. Op de touwtjes van de paalhula's, de touwen van de pontonhula’s en op de palen met hula’s werd geen vestiging van *C. gigas* waargenomen. Deze exotische oester heeft het westelijk deel van de Rotterdamse haven sinds de jaren 90 van de vorige eeuw gekoloniseerd. De natte biomassa (inclusief schelpen) van de mosselen op de paalhula’s was tussen de 4,4 tot 11,4 keer hoger vergeleken met de biomassa op referentiepalen. De biomassaproductie op de touwen van de pontonhula’s was dichtheidsafhankelijk en geschat is dat de optimale touwdichtheid tussen de 4 à 8 touwen per m^2 ligt. Ook werd aangetoond dat het voedsel door competitie beperkend was, omdat de biomassa (voornamelijk van de mossel) op de touwen van de pontonhula's van de rand van de hula tot aan het hart met 50% afnam. Het experiment toonde aan dat "ecological engineering" in het Rotterdamse havengebied met eenvoudige structuren als paalhula's en pontonhula's de sessiele biologische productie en de biodiversiteit enorm kunnen versterken. Dit heeft waarschijnlijk een positief effect op de lokale waterkwaliteit en kan, indien toegepast op grotere schaal, het ecosysteem van dit restant van het Rijn-Maasestuarium positief beïnvloeden.

In de synthese (hoofdstuk 7) zijn de resultaten van deze studie geplaatst in een breder perspectief en vergeleken met ontwikkelingen elders. De afname van het areaal van zachtsubstraatecotopen heeft zich in de meeste grote Europese estuaria voorgedaan, en ook zijn getijverschillen en de lengte van de zoutgradiënt in de laatste twee eeuwen dramatisch veranderd. Wereldwijd neemt de bezorgdheid toe over de uitbreiding van het verspreidingsgebied van de paalworm in relatie tot opwarming van de aarde. Veel studies worden uitgevoerd om schade door paalwormen te voorkomen. Het hula-experiment wordt herkend als een innovatieve methode om de habitat van havens te verbeteren. Meer eenvoudige maatregelen zijn beschreven die kunnen helpen de haven van Rotterdam in de richting van een "haven for estuarine nature" te loodsen.

Dankwoord



Een dankwoord beginnen is lastig want met wie moet je beginnen? Hoe heeft het allemaal zo ver kunnen komen? Het begon ongeveer 10 jaar geleden toen ik met Bram bij de Vaate sprak over het gaan opschrijven van mijn wederwaardigheden als zelfstandige. Hij bracht me in contact met Gerard van der Velde, mijn copromotor. Ik zeg bedankt Bram! Bij Gerard is het motto “Wie A zegt moet B zeggen”, en dus moet je afmaken waar je aan begonnen bent. Dat ging gelukkig nooit onder dwang, maar je hield hoe dan ook het gevoel dat je eraan moest werken. Gerard welgemeende dank aan jou voor de uitstekende begeleiding, het samenwerken, de discussies, de tips en de stimulans om door te gaan. Tijdens de doctoraalfase in Wageningen was dat wel anders! Waar waren die begeleiders en professoren toen eigenlijk? Enfin hun onzichtbaarheid heeft ongetwijfeld bijgedragen om als zelfstandige door te gaan in de aquatische ecologie. Henk Siepel bedankt dat je mijn promotor bent. Emiel van Velzen en Piet Jan Zijlstra mijn dank dat jullie bij de verdediging van het proefschrift mij ter zijde wilden staan.

Met studenten van de “Afdeling Dierecologie & Ecofysiologie” van de Radboud Universiteit is er gewerkt aan het project “Ecological Goals and Indicators”, onderdeel van het New Delta project “Ports and nature striking a new balance”. Resultaten die hier uit voortvloeiden zouden gebruikt worden voor dit proefschrift. Helaas er ging het een en ander mis en zal publicatie van de resultaten pas in 2014 plaats gaan vinden. Desalniettemin wil ik de voormalige studenten Saskia Meuffels, Cindy van Orsouw, Bas Budel, Daniël Bakker, Mireille Dorothaal en Sietse van der Zwart bedanken voor hun inzet. Hier moet ik zeker ook de analiste van de afdeling, Marij Orbons noemen die zich door de vele emmers en potten met steurgarnalen heen heeft weten te werken. Veel lof hier voor, ik ga er nog mee aan de slag.

Hoofdstuk 2 een verhandeling over de historische ontwikkeling van estuariene ecotopen in de Noordrand van het noordelijk deltabekken zou niet hebben kunnen worden geschreven zonder de door Ernst Lofvers, Waterdienst Rijkswaterstaat, Lelystad en Marjolein Bons, Meetdienst Rijkswaterstaat Zuid-Holland, Rotterdam aangeleverde gedigitaliseerde historische rivierkaarten. Ook hiervoor dank. Wie ik hier zeker niet mag vergeten is André de Kwaasteniet oud-medewerker van het Havenbedrijf Rotterdam NV die mij in 1997 alle tekeningen van de kademuren en oevers van Europoort en Maasvlakte 1 heeft aangeleverd, wat me op de gedachte van “petrifying the estuary” heeft gebracht. Maar ook Cor Mooiman oud-medewerker van het Havenbedrijf Rotterdam NV vergeet ik niet voor het aanleveren van allerhande gegevens omtrent de havenbekkens. Van onschatbare waarde was ook Peter Charpentier voor het opsnorren van soms vage literatuur uit duistere krochten in een tempo waarvoor op zijn minst een knieval uit dankbaarheid op zijn plaats is. Met dezelfde inzet heeft hij ook veel literatuur aangeleverd voor de overige hoofdstukken van dit proefschrift.

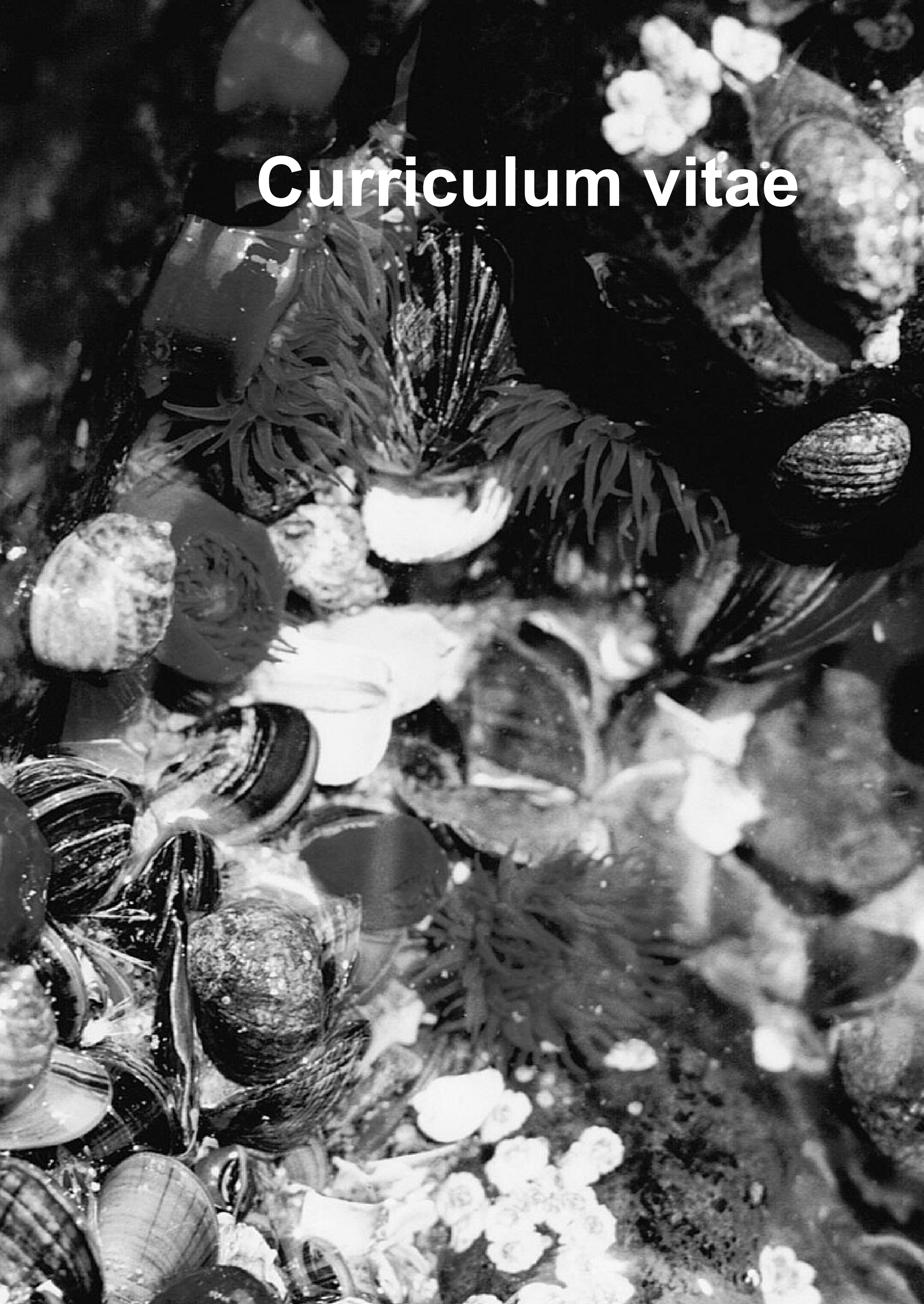
De paalwormartikelen die een groot deel van het proefschrift beslaan, zijn tot stand gekomen doordat medewerkers van het Havenbedrijf Rotterdam NV zich zorgen maakten om bevindingen omtrent dit dier in de haven van Bremerhaven. Mijn dank gaat uit naar Nicolette Ammerlaan, Piet Louwen, Sjaak Teeuwen, Maarten Meijler, Yme Ottema en Martin Minnaard, allen van het Havenbedrijf Rotterdam NV, voor het faciliteren van het onderzoek in de periode van 2003 tot en met 2009. Jan Saarloos van Firma Simons bv dank ik voor het maken van de plankjes voor het onderzoek en het beschikbaar stellen van grote hoeveelheden door paalworm aangetast hout uit de haven die mij wijsheid brachten en waarmee ik tevens verschillende jaren mijn huis heb kunnen verwarmen. Lambèr Hulsen van het Havenbedrijf Rotterdam NV zag erop toe dat de SIMONA-berekeningen goed verliepen en Vincent Beijk van Rijkswaterstaat leverde de omrekeningsfactoren voor de rivierafvoer aan, waardoor de klimaatseffecten op de verspreiding van de paalworm ingeschat konden worden. Beide heren, top!

Via het project “Ecological Goals and Indicators” heb ik Mindert de Vries van Deltares leren kennen. Hiervoor ben ik Pim de Wit van het Havenbedrijf Rotterdam NV die mij voor het project uitnodigde om mee te werken en denken dank verschuldigd. Ik bedank Mindert in het bijzonder, omdat ik eindelijk via hem mijn onderwaterhangendesubstratenideeën kwijt kon. Zijn enthousiasme heeft (en wellicht ook de riante medefinanciering via WINN-subsidie van Rijkswaterstaat) het havenbedrijf over de streep getrokken om het experiment in de haven aan te gaan. De financiële rompslomp, de coördinatie en alles wat rondom het project geregeld moest worden lag in handen van Sander Cornelissen van het Havenbedrijf Rotterdam NV en Bregje van Wesenbeeck van Deltares. Ik ben dankbaar dat ze dit allemaal in goede banen hebben weten te leiden. De paalhula’s zijn gemaakt door de mannen van Zeilmakerij de Bruijn & Meijer te Vlaardingen, die ik zeer erkentelijk ben voor het meedenken waardoor de duurzaamheid van deze hula’s van dien aard is dat deze na bijna 5 jaar nog ongeschonden rond de palen in Scheur- en Pistoolhaven zitten. Niet in de laatste plaats dank ik mijn vrouw Adrienne Woerdenbagch voor het snijden van de talloze touwtjes en touwen die in paalhula’s (10 km touw in 8339 touwtjes van 120 cm) en pontonhula's (1682 m touw in 1150 touwen van 40 tot 160 cm) zijn verwerkt, en het assisteren bij het veldwerk. De pontonhula’s zijn door ondergetekende zelf geconstrueerd maar zonder de hulp van een drietal

jongemannen zouden niet op tijd de 1150 touwen aan het netwerk kunnen zijn vastgemaakt. Goed werk is geleverd door Tim van Dorp, Jens Kooij en Rutger van Houwelingen. Dankbaar gebruik heb ik gemaakt van de veelzijdige technische vaardigheden van de Marcellen van Deltares, respectievelijk Grootenboer en Busink!
Het boven water halen van de monitoringsstrengen van de paalhula's was niet altijd even gemakkelijk. Ikzelf heb menigmaal vanaf een werkponton met een assistent zittend op mijn benen om niet de haven in te glijden tot aan mijn middel ondersteboven in het water gehangen om ze te pakken te krijgen. Marinus Eigenraam is op een warme zomerdag spontaan de Pistoolhaven ingedoken omdat hij geen andere mogelijkheid zag de strengen te pakken te krijgen. Een uitkomst bij de laatste bemonstering was natuurlijk de oud-medewerker van de "Afdeling Dierecologie & Ecofysiologie" Martin Versteeg die zich in zijn droge duikpak hees om op professionele wijze de klus te klaren. Martin fantastisch, het heeft veel aan de resultaten toegevoegd! Hier nogmaals lof voor Marij Orbons voor het determineren van de beestenboel die tussen de mosselen van de hula's zat.
Het hulaproject zou niet hebben kunnen plaatsvinden zonder de belangeloze medewerking van het Loodswezen en Smit Harbour Towage. Hierbij hebben Peter van Dijk van het Loodswezen, Jan-Pieter Steunebrink en André van der Kaaij, beiden van Smit, een belangrijke rol gespeeld.

En natuurlijk ook dank aan hen die verder nog een bijdrage aan dit proefschrift hebben geleverd.

Curriculum vitae



Peter Paalvast werd op 10 februari 1952 als 12-ponder (circa “one Stone”) geboren in de wijk ’t Stort te Maassluis. Na drie maanden verhuisde het gezin naar Vlaardingen. Hier werd de lagere school en het leeuwendeel van de HBS doorlopen. Na een jaar praeses van de leerlingenvereniging Universia van het Groen van Prinstererlyceum te zijn geweest, werd het schoolgaan een periode wat minder interessant gevonden. Uiteindelijk werd eindexamen gedaan op het Spieringshoeklyceum te Schiedam. De motivatie om biologie te gaan studeren kwam mede voort uit de discussies tijdens de biologielessen van Joop van Lenteren (thans emeritus hoogleraar Entomologie Wageningen University) en Koos Slob (thans emeritus hoogleraar in de fysiologie en pathofysiologie van de seksualiteit aan de Erasmus Universiteit Rotterdam) over milieuvervuiling en overbevolking en wat daar aan te doen. In 1972 werd aangevangen met de studie biologie aan de Landbouwhogeschool te Wageningen (nu Wageningen University). Hele dagen college en practica, avondpractica en werkcollege op zaterdagochtend was toen nog gewoon. Na het behalen van het kandidaatsexamen (met 50% extra studiepunten) werd de doctoraalfase in 1977 begonnen met elektrofysiologisch onderzoek (chemoreceptie) aan het koolwitje (*Pieris brassicae*) in relatie tot de eiafzetting op zijn gastplant onder begeleiding van prof. dr. Louis Schoonhoven. Hierna werd 6 maanden stage gelopen op het biologisch station Tour du Valat in de Camargue, waar naast het meedraaien in het gedragsonderzoek aan paarden onder leiding van dr. Patrick Duncan, een eigen onderzoek werd gedaan naar het markeringsgedrag van de paarden met urine en feces. Dit leverde de eretitel “merdologiste de la Camargue” op. In 1978 werd begonnen aan een studie betreffende de inter- en intraspecifieke relaties van zeekraal binnen de gezoneerde vegetatie van de schorren aan de Oosterschelde met dr. ir. Wim Beeftink van het toenmalige Delta Instituut voor Hydrobiologisch Onderzoek (nu Koninklijke NIOZ) als begeleider. De vrijheid was groot zodat een bijna geheel eigen invulling aan het onderzoek kon worden gegeven. De studie werd afgesloten met een onderzoek voor STINAPA Nederlandse Antillen (gestimuleerd door dr. Ingvar Kristensen) onder verantwoording van dr. Chris Geerlings naar het voorkomen en het gedrag van geiten in het Christoffelpark te Curaçao en het Washington Slagbaai Nationaal Park te Bonaire, waarvan de gegevens zijn gebruikt voor het opstellen van een begrazingsonderzoek in beide parken. Gedurende de studie waren er voor een cumulatieve duur van een ongeveer een jaar aanstellingen als student-assistent bij de vakgroepen Experimentele Diermorfologie en Celbiologie, Fysiologie der Dieren en Plantensystematiek aan de Landbouwuniversiteit Wageningen.

Na het behalen van het doctoraalexamen in september 1979 zou begin 1980 begonnen worden met een promotieonderzoek bij de vakgroep Natuurbeheer van de Landbouwhogeschool naar de nichedifferentiatie van grote herbivoren in

Nigeria. Op het laatste moment bleek daar geen geld meer voor beschikbaar te zijn. Een jaar werd als onbezoldigd gastmedewerker bij de vakgroep Algemene Visteelt en Visserij doorgebracht, en werd een onderwijsbevoegdheid in de biologie behaald. Na het behalen van de bevoegdheid tot lesgeven werd tien maanden lang voor enkele uren gewerkt voor de Gemeentelijke Stichting Avondlyceum te Rotterdam en de Openbare School voor MAVO te Rozenburg.
In 1982 werd een aanstelling als docent in het middelbaar en hoger laboratoriumonderwijs aan de Stichting van Leeuwenhoek Instituut te Delft aanvaard. Deze aanstelling zou duren tot en met 1990 waarbij de arbeidsovereenkomst een kleine 20 keer werd ontbonden en even vaak weer werd overeengekomen als gevolg van splitsing in MBO en HBO en veelvuldige fusies met andere onderwijsinstellingen. In de periode 1990-1991 werd een jaar aan de Hogeschool Zeeland gedoceerd en een bijdrage geleverd aan het curriculum voor de opleiding Aquatische Ecotechnologie.
Prof. dr. Marinus Werger van de Universiteit van Utrecht was het die in 1983 adviseerde eens te gaan praten met de afdeling Terreinbeheer van de Duinwaterleiding van 's-Gravenhage (nu Dunea) om daar als zelfstandige vegetatiekundig onderzoek te gaan doen. Hier was echter geen ruimte voor, maar wel voor onderzoek naar de samenstelling van de vispopulaties in de infiltratievijvers in het door het bedrijf beheerde duingebied. Hiermee was in feite Ecoconsult geboren. Tot op heden zijn onder de Ecoconsultvlag een honderdtal veld- en bureaustudies verricht voor onder andere Rijkswaterstaat, LNV, Havenbedrijf Rotterdam NV, Deltares, Hoogheemraadschap Hollands Noorderkwartier en GIP-Seine Aval te Rouen in Frankrijk.
Van 1994 tot en met 2010 is jaarlijks een bijdrage geleverd aan de masteropleiding IMACOF (Ingénierie des Milieux Aquatiques et des Corridors Fluviaux) van de "Université François Rabelais de Tours" in Frankrijk in de vorm van colleges en excursies.
Peter Paalvast is getrouwd met Adrienne Woerdenbagch, heeft een zoon, een dochter, en is opa van Tom (11 september 2012) en Daniël (5 februari 2014).

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