Chapter 7

Synthesis

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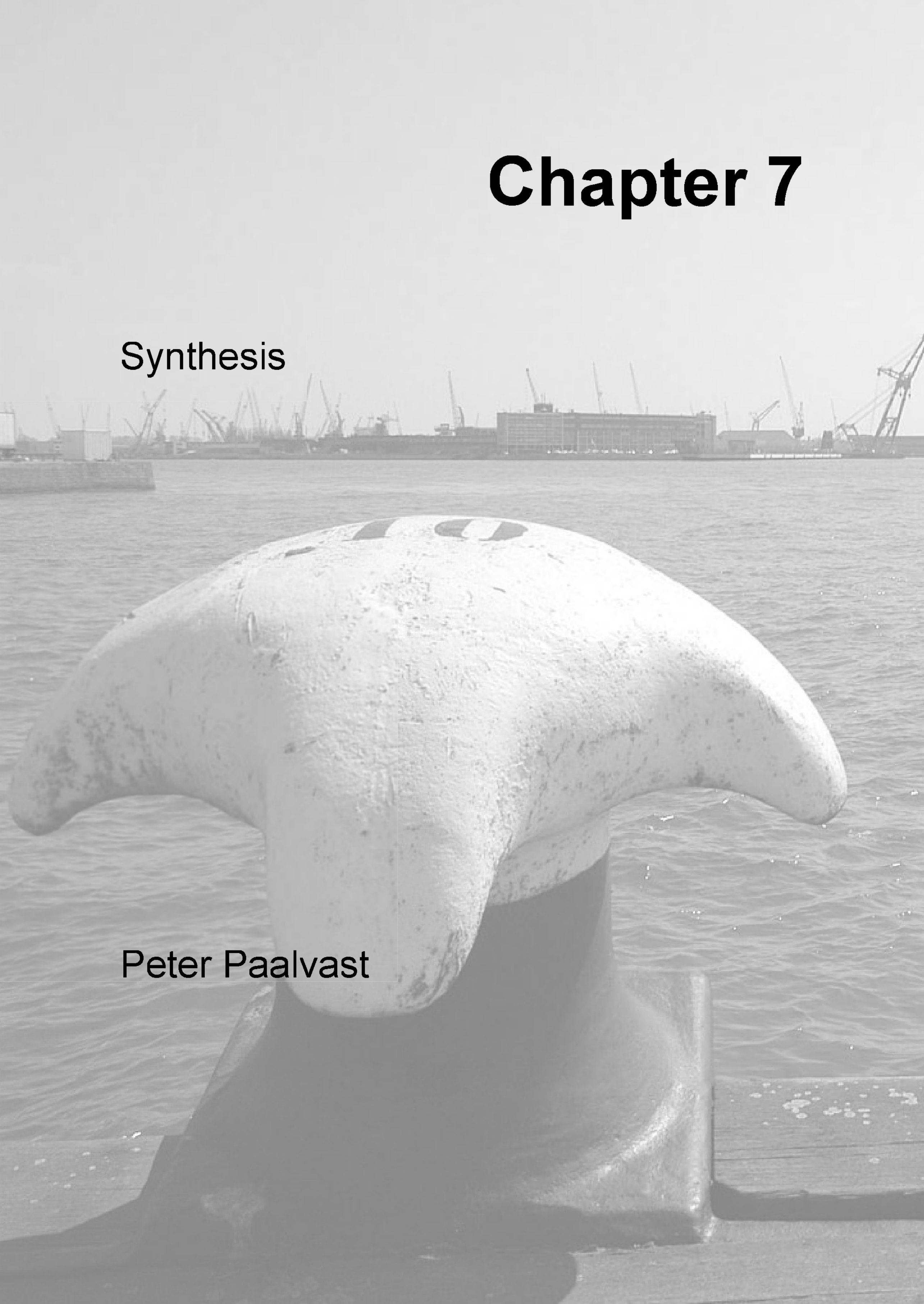

Broader perspective and developments elsewhere

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 19th and 20th 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 20th 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).

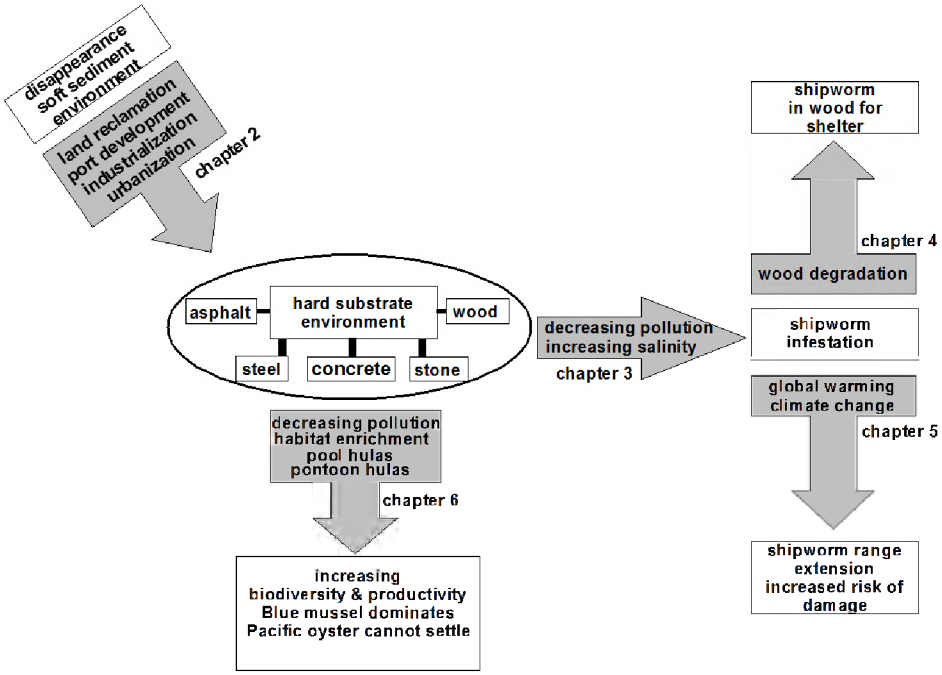

Figure 1 Main results of this study.

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.

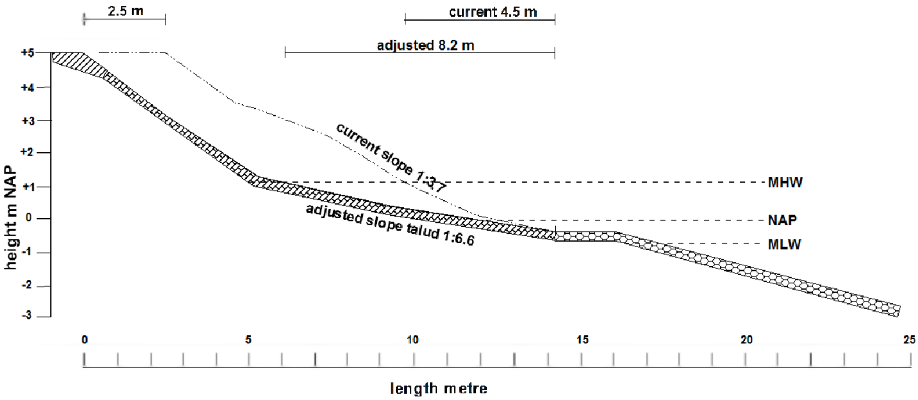

Figure 2 Example of adjusting the slope of a common type of retaining wall in the polyhaline harbours of the port of Rotterdam. MHW=mean high water level, MLW=mean low water level, NAP=Amsterdam Ordnance Datum. (after Paalvast, 1998).

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).

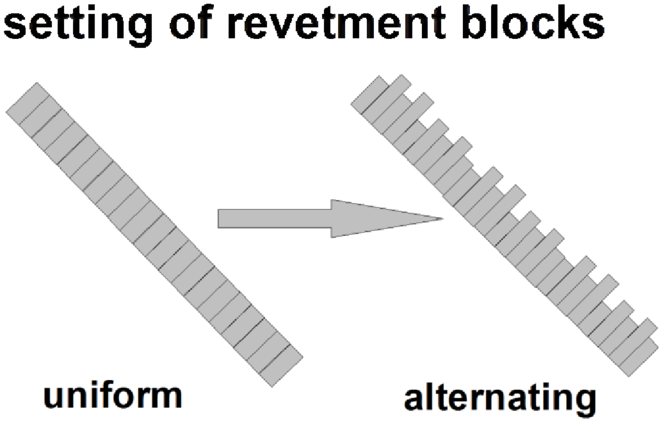

Figure 3 Setting revetment blocks in an alternating manner to create a more differentiated habitat on the slope of retaining walls.

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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