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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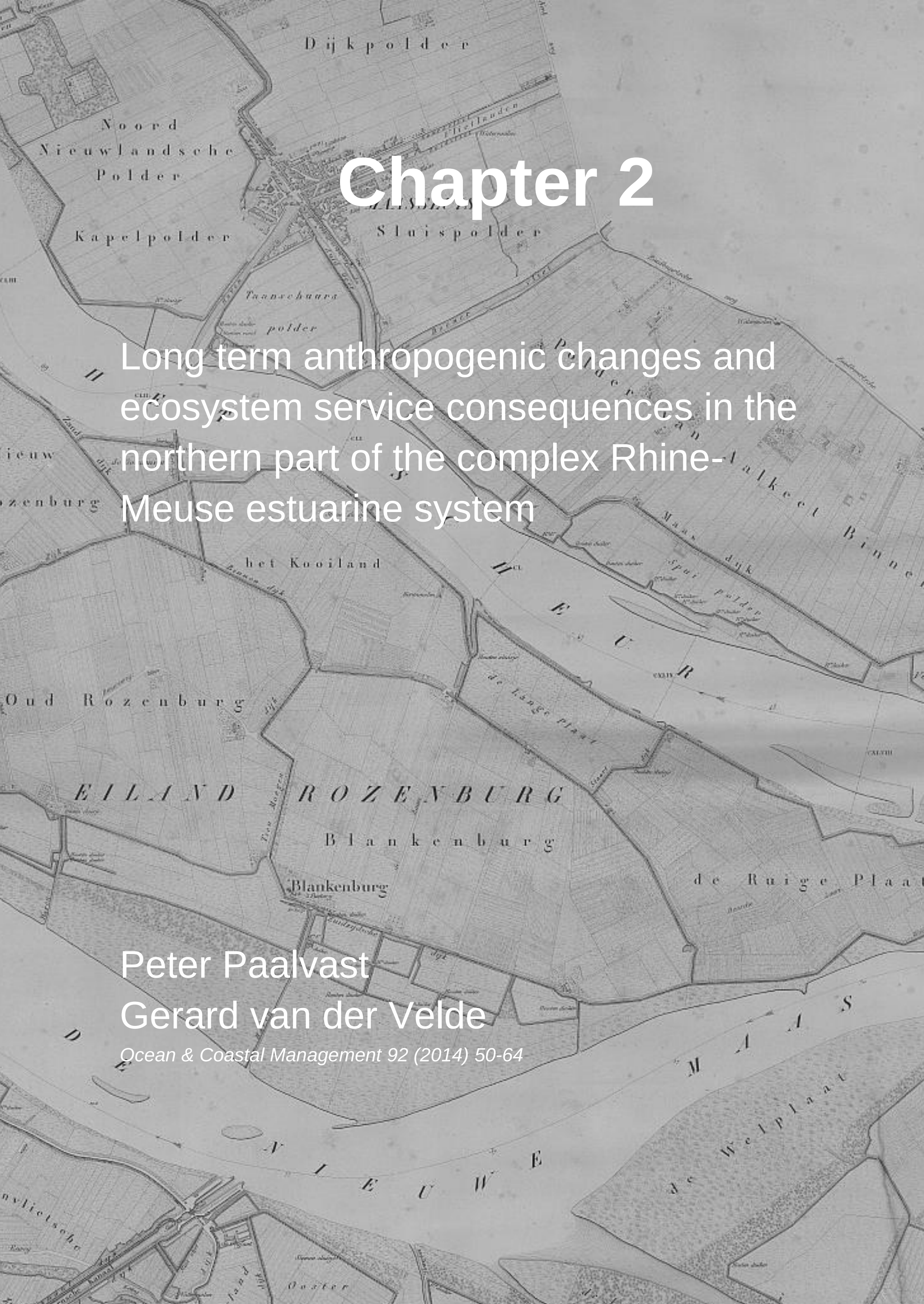

Abstract

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

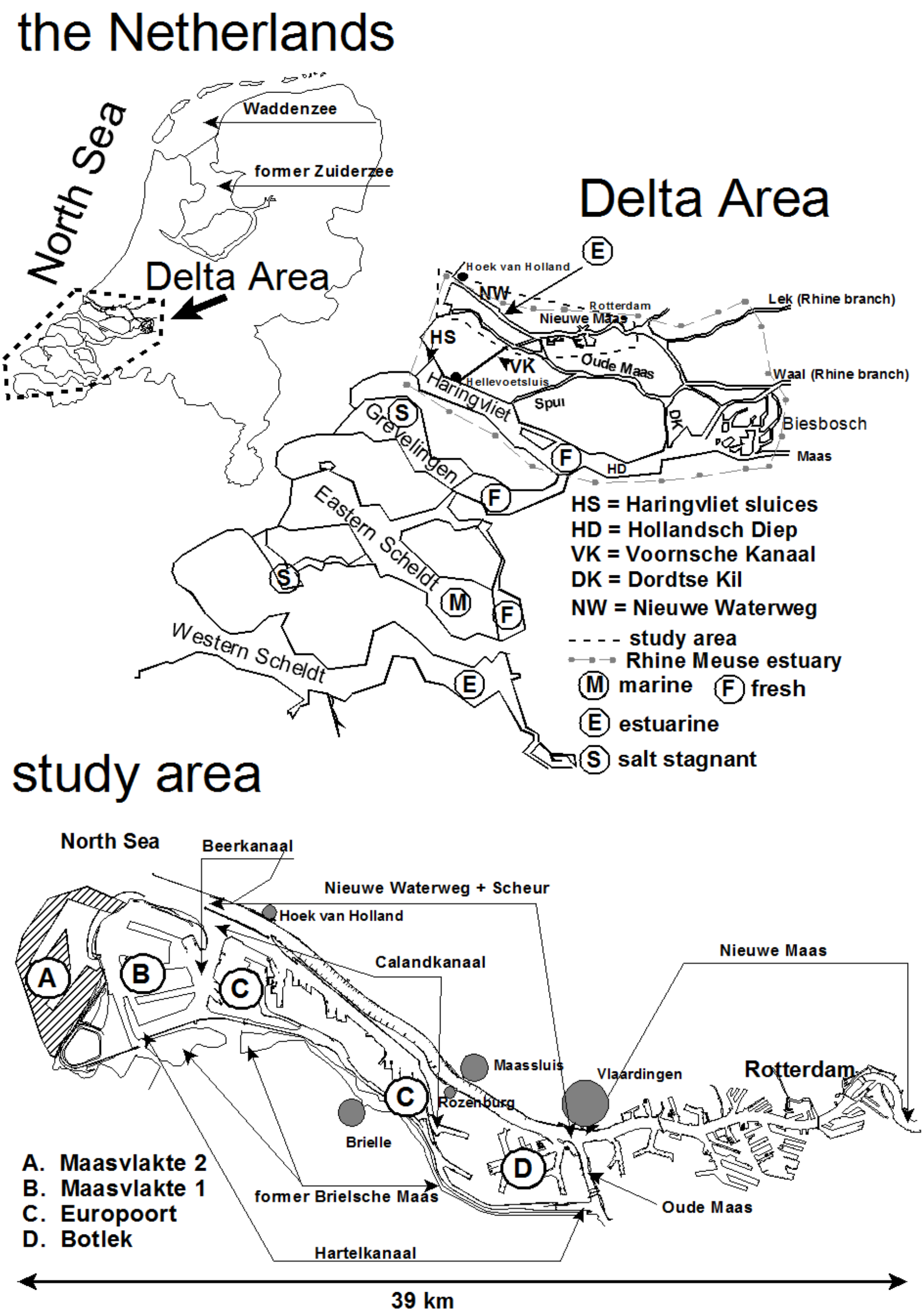

Figure 1 The location of the study area in the Delta Area in the Netherlands. The Lek, Waal and Oude Maas are distributaries of the river Rhine. Maas=Meuse.

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.

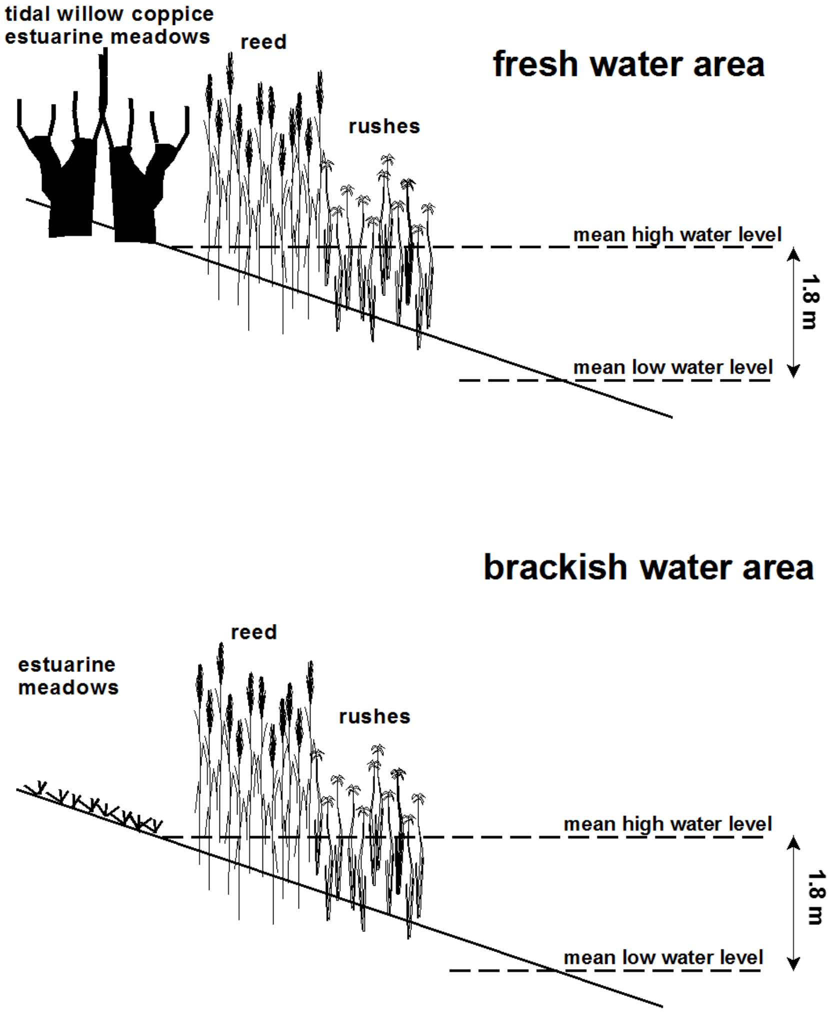

Figure 2 Zonation of ecotopes in the fresh and brackish water part of the Rhine-Meuse estuary.

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 13^{th} 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).

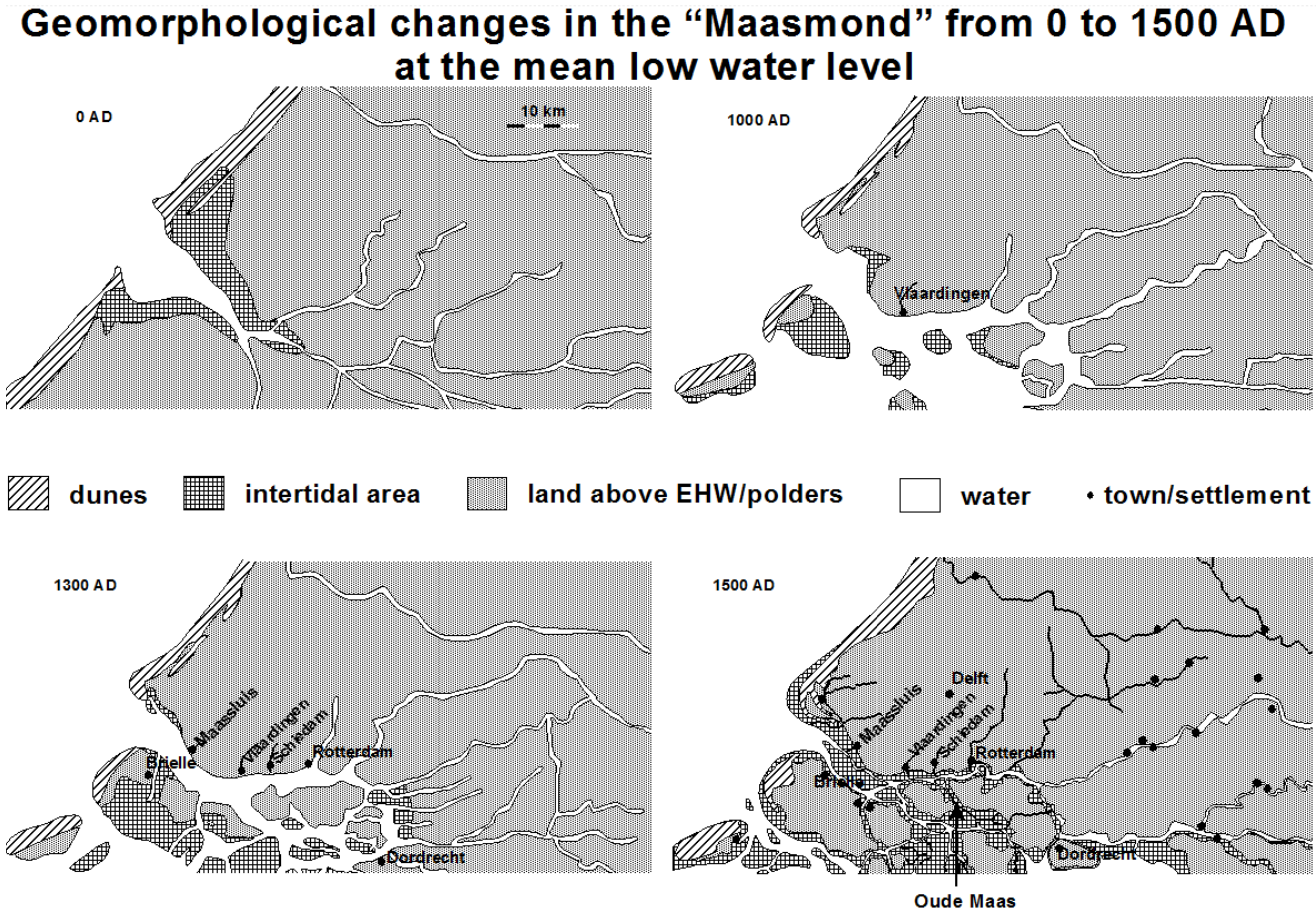

Figure 3 Geomorphological changes at the mean low water level in the “Maasmond”, the mouth of the Rhine-Meuse estuary between 0 and 1500 AD (after Zagwijn, 1991). EHW = extreme high water level.

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.

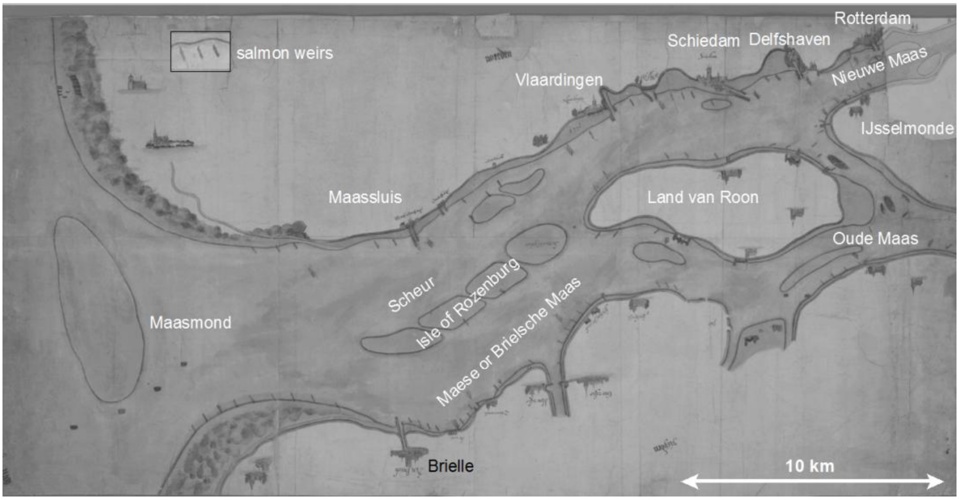

Figure 4 Map of the northern part of the Rhine-Meuse estuary around 1500 AD (author unknown).

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

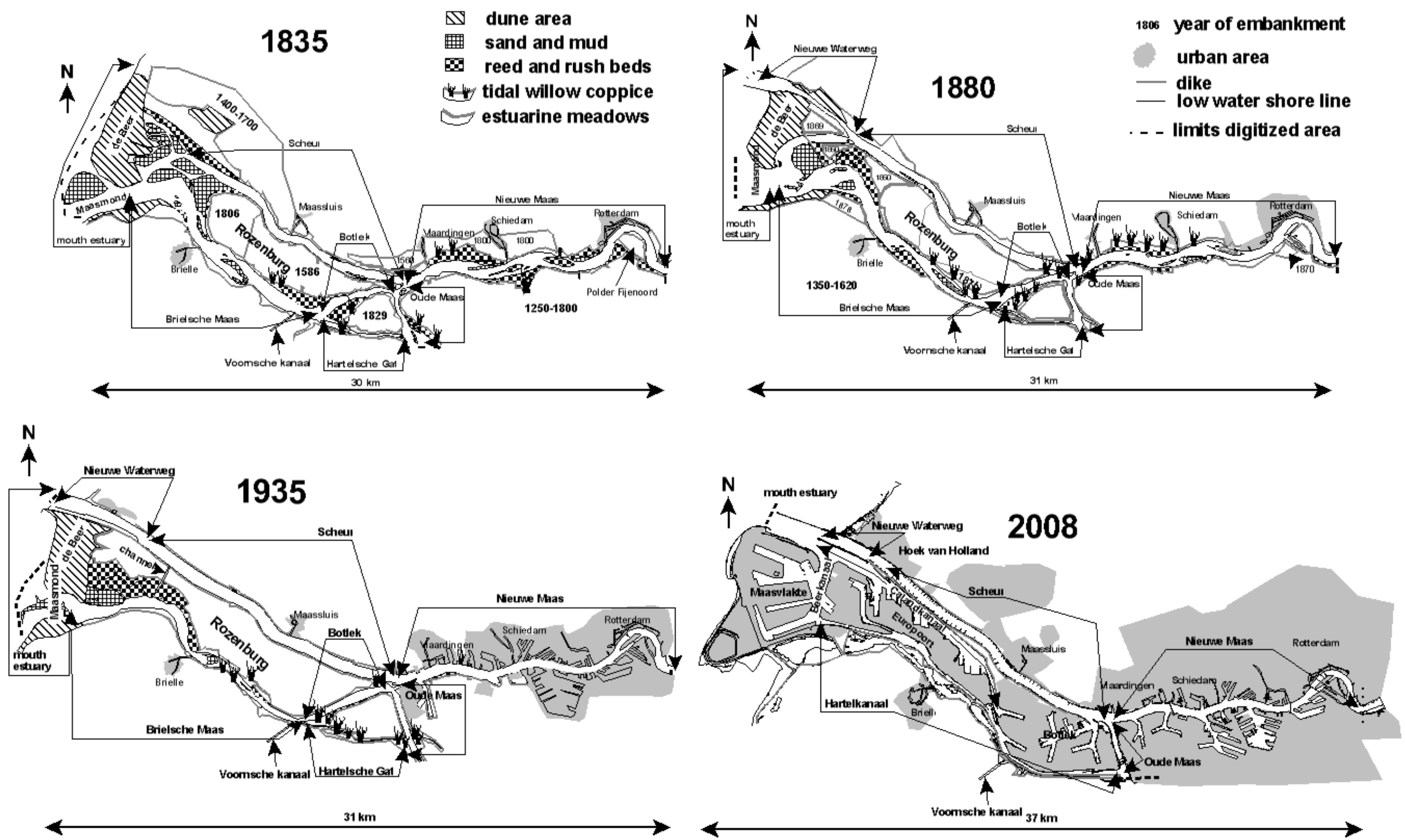

Figure 5 Changes of estuarine ecotopes between 1835 and 2008 in the Rhine-Meuse estuary.

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.

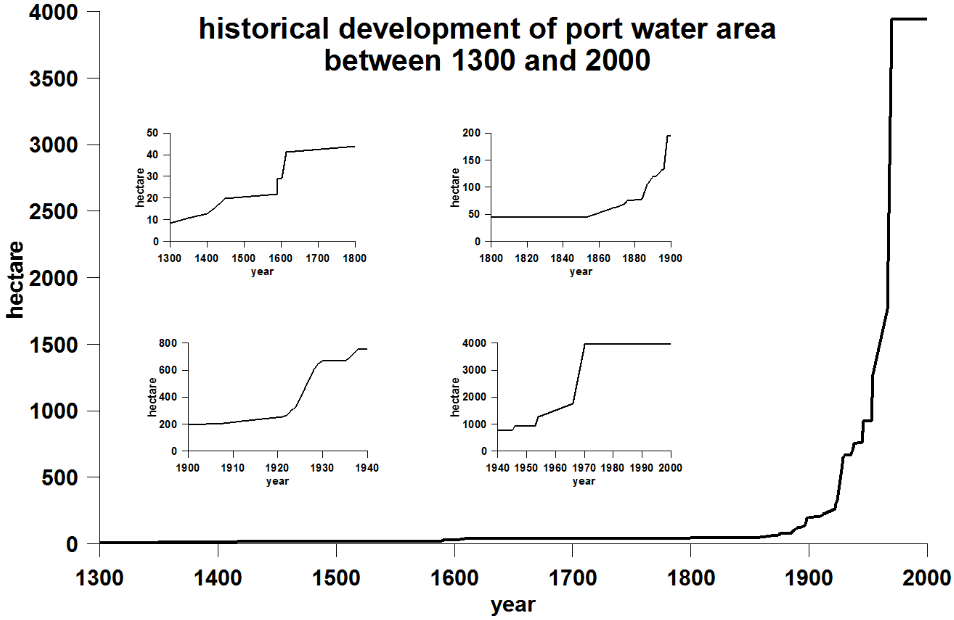

Figure 6 Historical development of the port water area in the northern part of the Rhine-Meuse estuary between 1300 and 2000.

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.

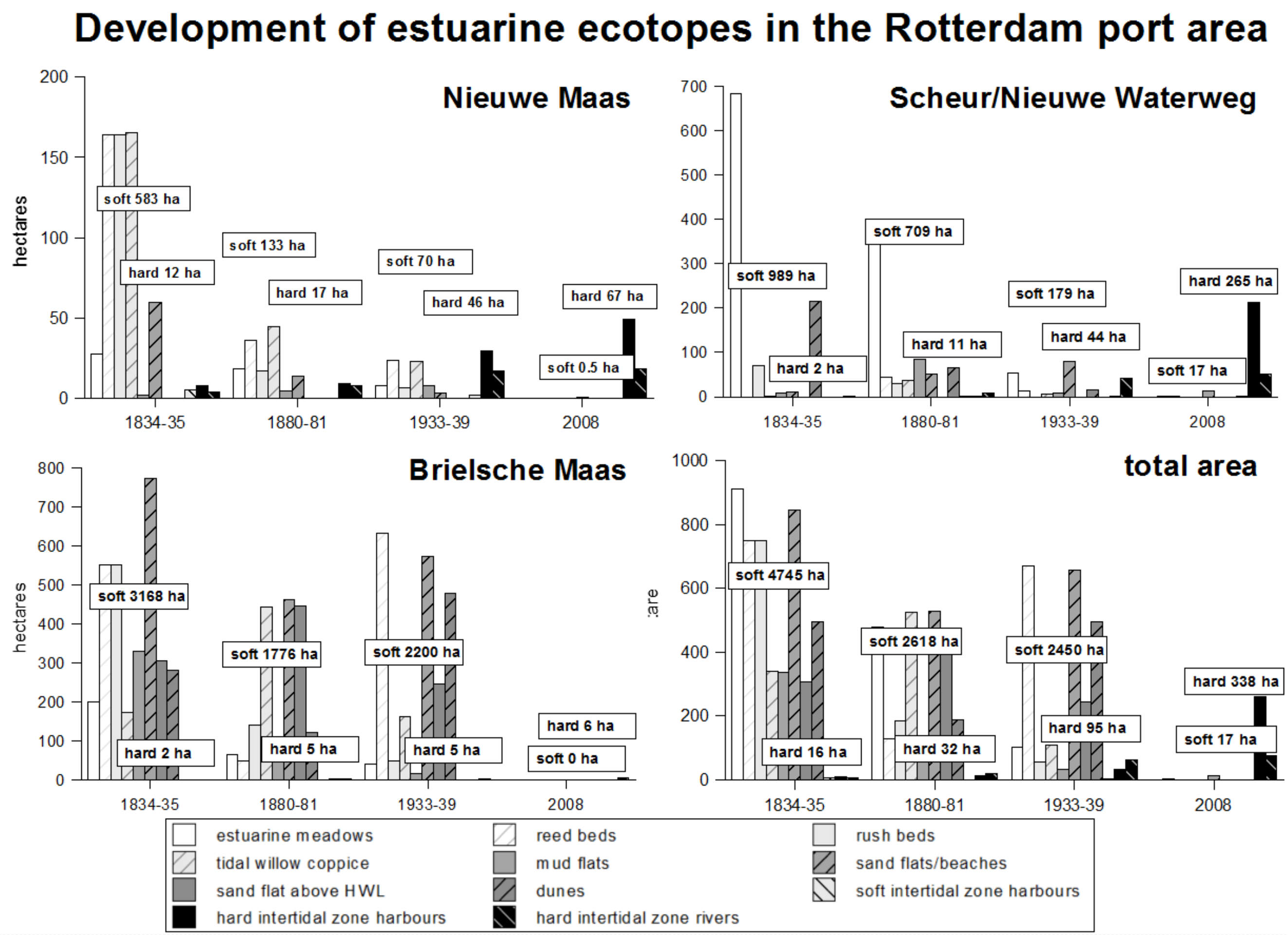

Figure 7 Development of estuarine ecotopes in the Rotterdam port area (nowadays called Rijnmond).

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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